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Fisheries Research 62 (2003) 307–328
FISHERIES RESEARCH
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Interactions of Atlantic salmon in the Pacific Northwest IV. Impacts on the local ecosystems

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Abstract

The paper begins with the introduction of Atlantic salmon into the local ecosystems of the Pacific Northwest (Puget Sound), and describes potential interactions with native salmonids. Specific sections review possible hybridization between Atlantic and Pacific salmon, genetic dilution and alteration of the gene pool, the colonization of the aquatic environment by Atlantic salmon, and finally the interactions of wild salmon and genetically altered transgenics. This is followed by possible epidemics and transmission of waterborne disease, and reviews the potential for cultured Atlantic salmon, a non-native species, to introduce new diseases into the local ecosystem. There are nine specific items, from the diseases which might be involved, to potential interactions, and current policies for disease control. After a review of the potential ecological impacts in the Pacific Northwest, specifically the interaction with Pacific salmon and predation, there are three parts on the effects of artificial propagation practices in the region in general, the impacts of the introduction of various non-indigenous salmonid species, and a comparison of escapes or releases of propagated Atlantic and Pacific salmon. The last part examines the potential effects of Atlantic salmon vis-à-vis the Biological Status Reviews of west coast Pacific salmon stocks carried out by the National Marine Fisheries Service. The review ends by summarizing the varying degrees of risk carried by these issues.
Published by Elsevier Science B.V.

Keywords: Atlantic salmon; Salmonids; Pacific Northwest ecosystems; Colonization; Predation; Genetic interactions; Waterborne diseases; Risks

1. The artificial propagation of salmonids in the Pacific Northwest

1.1. Background

Artificial propagation of salmon and trout in the Pacific Northwest has come under increasing scrutiny in recent years. This is due to the recognition that hatchery-cultured salmon and trout may have the potential to impact natural populations adversely. Although the weight of attention has been focused on the extremely large complex of federal, state, tribal, and cooperative hatcheries in Alaska and the western states, concerns about the potential adverse impacts of private trout and salmon culture in Washington have also been described by Ellis (1996), and Alverson and Ruggerone (1997).

Concerns about genetic interactions, the transmission of disease, and ecological interactions are most commonly voiced. In 1997, e.g., the Pollution Control Hearing Board of the State of Washington (PCHB) heard testimony that Atlantic salmon had the potential to hybridize with Pacific salmon, based on unpublished Canadian laboratory studies, and that it was possible the 369,000 Atlantic salmon which escaped into Puget Sound in 1996 would produce 10 million

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0165-7836/03/$ – see front matter. Published by Elsevier Science B.V.
doi:10.1016/S0165-7836(03)00066-3

healthy smolts in local rivers. Subsequently, in 1999, the Alaska Department of Fish and Game (ADF&G) published a press release that escaped Atlantic salmon from west coast salmon farms would compete with wild salmon, and spread diseases and parasites for which Pacific salmon had little resistance.

1.2. The origin and disease status of the Atlantic salmon stocks in Puget Sound

In 1971 scientists from the National Marine Fisheries Service (NMFS) at the Manchester Research Station began testing the feasibility of rearing New England stocks of Atlantic salmon in seawater net-pens in Puget Sound to provide 3.5 million eyed eggs annually for restoring depleted runs in southern New England. Between 1971 and 1983, the station received eggs from many North American stocks, including the Grand Cascapedia River in Quebec (via Oregon State), and the Penobscot, Union, St. John, and Connecticut Rivers in the United States.

Each delivery of eggs was examined in accordance with federal regulations and certified by federal pathologists to be free of bacterial and viral pathogens prior to transfer from New England to Washington. However, few eggs were ever sent back as a panel of New England state and federal fisheries officials determined in 1984 that raising Atlantic salmon in Puget Sound rendered the eggs unfit for transfer back to the east coast because of the risk of introducing Pacific salmon diseases to New England Atlantic salmon populations.

As a result of this decision, millions of Atlantic salmon eggs originally meant for New England restoration programs were available for distribution to salmon farmers in Washington. These eggs proved to be beneficial to the local industry as, by this time, it was clear from work in Norway and Scotland, that Atlantic salmon were superior to Pacific salmon in all aspects of culture, including survival to hatching, growth rate in fresh and sea water, and resistance to infectious diseases.

2. Genetic interactions of artificially propagated Pacific and Atlantic salmon

A major concern with artificial propagation in general, and farming of Pacific salmonids and Atlantic salmon in particular, is the potential genetic effects of deliberate releases and inadvertent escapees on the native salmonids. For the salmon farming industry in British Columbia, Canada, where both Pacific and Atlantic salmon are extensively farmed, the British Columbia Salmon Aquaculture Review published by the Environment Assessment Office (EAO, 1997) listed four major areas of concern:

- Hybridization between Pacific and Atlantic salmon;
- Genetic dilution and alteration of the wild salmonid gene pool;
- Colonization by Atlantic salmon;
- Interactions between wild salmon and genetically altered transgenics.

These concerns are both geographically and species specific. Across the border in Puget Sound, the concern is only with farmed Atlantic salmon, as Pacific salmon, with rare exception, are not cultured by private enterprises.

2.1. Hybridization

No genetic interactions between Atlantic and wild Pacific salmon have been reported in the Pacific Northwest. Similarly, under controlled and protected laboratory conditions where survival of hybrid offspring should be optimized, viable hybrids between Atlantic and Pacific salmonid species are difficult to produce. Refstie and Gjedrem (1975), Sutterlin et al. (1977), and Blanc and Chevassus (1982) found that crosses between Atlantic salmon and rainbow trout failed to produce any viable progeny. A similar lack of vitality was observed in pairings of Atlantic salmon and coho salmon (Chevassus, 1979), and Atlantic salmon and pink salmon (Loginova and Krasnoperova, 1982). Gray et al. (1993) attempted to produce diploid and triploid hybrids by crossing Atlantic salmon with chum and coho salmon, and rainbow trout. All embryos died in early developmental stages, leading to the conclusion that hybridization of Atlantic salmon with Pacific salmon species was unlikely to happen.

Recently, two pilot studies from British Columbia have provided more data regarding the lack of genetic compatibility between Atlantic and Pacific salmon (R. Devlin, Department of Fisheries and Oceans (DFO), Canada, reported in Alverson and Ruggerone, 1997). In the first study, using a small number of eggs, crosses with Atlantic salmon produced a few hybrids with pink salmon, but no hybrids with coho, chum, chinook, sockeye salmon, and rainbow trout. In the same experiment, by contrast, the interspecific crosses between Oncorhynchus species produced hybrids to hatch ranging from 10 to 90% in 15 of the 42 crosses, with each species of Pacific salmon readily produced hybrids with between two and five other Pacific salmon species, confirming previous observations in this genus (Foerster, 1935; Seeb et al., 1988). Moreover, because of dissimilar natural spawning times between Atlantic salmon in the fall, and steelhead in the spring, this particular cross was performed using cryopreserved Atlantic salmon sperm. In the second study, using a larger number of eggs and involving crosses between Atlantic salmon and rainbow and steelhead trout, coho, chum, chinook, and pink salmon, a few hybrids were produced. Cryopreserved Atlantic salmon sperm was again used for the cross with cutthroat trout, which spawned naturally in winter. Approximately 6.1% of the Atlantic salmon × steelhead, and 0.01% of the pink salmon × Atlantic salmon hybrids survived to the hatching stage.

These results were cited as evidence of Atlantic salmon's 'hybridization potential' before the PCHB in 1998, but the board found there was no reasonable potential for hybridization between escaped Atlantic salmon and native Pacific salmon in Puget Sound based on current knowledge and behavior (PCHB, 1998). The Atlantic salmon × steelhead hybrids could only be produced carefully in controlled experiments in vitro, and actual hybridization would probably not happen under natural conditions in western Washington, where cultured Atlantic salmon stocks have finished spawning by the end of November and wild steelhead spawn between mid-March and mid-June. Therefore, there is virtually no window of opportunity for Atlantic salmon to spawn with local wild, native steelhead outside the laboratory.

In discussions regarding the ecological interactions between farmed and wild salmon at a symposium on aquaculture and the protection of wild salmon, held at Simon Fraser University in Vancouver, in 2000 (cited by Waknitz et al., 2002), participants suggested that spawning escaped Atlantic salmon may produce precocious male Atlantic salmon which might attempt to breed with Pacific salmon. They hypothesized that these precocious males, while not actually capable of producing hybrids, might produce genetic disturbances by interfering with wild salmonid breeding behavior. For example, by beating Pacific salmon males to a redd, the resulting non-viable eggs would reduce the number of juvenile salmonids available for recruitment in depressed populations.

Although this scenario could possibly occur in some locations, it is improbable in the tributaries of Puget Sound for a number of reasons. First, salmon farmers in Puget Sound use Atlantic salmon derived from stocks provided to them by NMFS in the mid-1980s, primarily Penobscot River and Grand Cascapedia River strains. The Penobscot River hatchery strain is know to have a remarkably low incidence of early maturity, either after 1 or 2 years in freshwater (precocious male parr), or at 2 or 3 years of age (1 year at sea), known as grilse (Ritter et al., 1986). As age at maturity is a genetically inherited trait, which can then be influenced by changes in environmental conditions (Randall et al., 1986), the Penobscot River Atlantic salmon strain now used in Puget Sound salmon farms began with an especially low potential for adverse impacts from precocious males, assuming that naturally spawned juvenile male Atlantic salmon ever become numerous in Puget Sound tributaries.

Second, smoltification and early male maturity are mutually exclusive events (Thorpe, 1986). Precocious Atlantic salmon parr do not survive transfer to full strength seawater, due primarily to the fact that they have invested their metabolic resources in gamete production instead of acquiring the ability to osmoregulate in seawater. Therefore, in Puget Sound-domesticated Atlantic salmon populations, precocious parr are directly selected against in every generation at the time of transfer to seawater, where they are eliminated from that particular brood.

Third, protocols common to salmon farming also select directly, if inadvertently, against the production of precocious male Atlantic salmon in the Pacific Northwest. To reduce freshwater rearing costs, local salmon farmers cull juveniles which do not smolt at 1 year of age. This selects against early maturity, because 1-year-old smolts are known to produce fewer precocious parr and grilse than 2-year-old smolts (Ritter et al., 1986). Furthermore, Atlantic salmon that mature as grilse after only 1 year in seawater are not retained for brood stock by growers in Puget Sound, because fish which never grow to a large size are not as profitable as those that do. Grilse are known to produce more precocious parr than older Atlantic salmon (Ritter et al., 1986).

While viable hybrids between Atlantic salmon and the Pacific salmonid species have been difficult to produce in the laboratory and do not occur under natural conditions, hybrids between Atlantic salmon and the brown trout, a sympatric species, are relatively successful. Viable Atlantic salmon × brown trout hybrids have been produced in the laboratory by, inter alia, Suzuki and Fukuda (1971), Refstie and Gjedrem (1975), Blanc and Chevassus (1982) and Gray et al. (1993).

Successful hybridization under natural conditions has been reported for Europe where brown trout are native, and also in North America where the brown trout has been introduced (Verspoor and Hammar, 1991). The frequency of natural hybridization in Europe and North America ranges from 0.1 to 13.2% of juveniles in river systems (Jordan and Verspoor, 1993), and appears to be increasing relative to pre-aquaculture levels (Hindar et al., 1998). McGowan and Davidson (1992) cite the breakdown in pre-reproductive isolating mechanisms (abundance of mature Atlantic parr) as the principal mechanism for natural hybridization. Hindar et al. (1998) reported that, although a disproportionate number of hybrids were the product of matings involving Atlantic salmon females, there was no evidence that escaped farmed Atlantic salmon females produced more hybrids than wild females. Youngson et al. (1993), on the other hand, had previously reported that escaped females in rivers in western and northern Scotland hybridized with brown trout more frequently. Wilkins et al. (1993) found that male hybrids were fertile and, when back-crossed with female Atlantic salmon, produced about 1% diploid progeny. Galbreath and Thorgaard (1995) reported that back-crosses between male diploid, male triploid, and female diploid Atlantic salmon × brown trout hybrids and both parental species produced either non-viable or sterile progeny.

No natural hybrids between Atlantic salmon and Pacific salmonids have been reported in Europe, despite the fact that introduced rainbow/steelhead trout, brook trout, coho salmon, and pink salmon have all established naturalized populations within the native range of Atlantic salmon throughout the European continent (MacCrimmon and Campbell, 1969; MacCrimmon, 1971; Berg, 1977; Lever, 1996). Similarly, no hybrids between Atlantic salmon and brown trout, rainbow trout, or brook trout have been reported in South America or New Zealand, even though all four of these species are not native to those locations (MacCrimmon, 1971; Lever, 1996).

The propensity of Atlantic salmon to produce successful hybrids with brown trout and not with the Pacific salmonids may be related to the phylogenetic distances that exist between the two groups. Neave (1958) postulated that the putative ancestors of the Salmo group migrated to the Pacific 600,000–1,000,000 years ago, were subsequently isolated by land bridges, and evolved to the ancestral Oncorhynchid form. The ancestral Oncorhynchid form subsequently developed to form the separate *Oncorhynchus* species (Simon, 1963). McKay et al. (1996), based on DNA sequence analysis of growth hormone type-2 and mitochondrial NADH dehydrogenase subunit three gene, estimated that, at a minimum, the major divergence between the genus *Salmo* and the genus *Oncorhynchus* occurred 18 million years ago, while speciation within the genus *Oncorhynchus* began about 10 million years ago.

Attesting to their phylogenetic similarity, interspecific hybrids within the Oncorhynchids are relatively successful. Foerster (1935) was among the first to report successful hybrids between controlled mating of sockeye, chum, pink, and chinook salmon. Since then, limited occurrences of natural hybrids have been reported among anadromous salmonids. Bartley et al. (1990) reported on natural hybridization between chinook and coho salmon in a river in northern California, and Rosenfield (1998) reported a natural pink × chinook hybrid from the St. Mary's River in Michigan. On the other hand, hybridization between introduced rainbow trout and native cutthroat trout appears to be almost ubiquitous throughout the interior part of western North America, and has been enormously detrimental to the latter species according to Gresswell (1988) and Behnke (1992).

2.2. Genetic dilution and alteration of the wild salmonid gene pool

Adverse genetic and ecological effects due to releases or escapes of artificially propagated Atlantic salmon from public hatcheries and private net-pens on wild Atlantic salmon populations in Norway, Scotland, Ireland, and the Canadian Maritimes have been reported. For wild Atlantic salmon these include a reduction in their genetic adaptability and capacity to evolve as a result of interbreeding with artificially propagated fish, and direct competition for food and space (Einum and Fleming, 1997; Gross, 1998).

Such adverse effects only happened in those locations because both the cultured and wild fish were Atlantic salmon. On the west coast of North America, escaped Atlantic salmon do not have congeneric wild individuals with which to interact. In the Pacific Northwest region, the release of hatchery Pacific salmon has the greater potential to produce impacts on native Pacific salmon, analogous to those found between cultured and wild Atlantic salmon in Europe and eastern North America.

Adverse genetic and/or ecological interactions on local wild salmon populations from artificially propagated Pacific salmon have been well-documented in EAO (1997) and the Biological Status Reviews of west coast Pacific salmon stocks carried out by NMFS since 1995 (see Section 8). No detrimental effects related to Atlantic salmon have been reported in western North America.

2.3. *Colonization by Atlantic salmon*

In the past century there have been numerous attempts in the United States and elsewhere to establish Atlantic salmon outside its native range. These attempts involve at least 34 different states, including Washington, Oregon, and California. None of these efforts was successful. MacCrimmon and Gots (1979) subsequently reported that no reproduction by Atlantic salmon was observed in the waters of these states, reconfirmed twenty years later by Dill and Cordone (1997) and Alverson and Ruggerone (1997).

It also appears difficult to reintroduce Atlantic salmon to their native rivers. In the last 100 years, Atlantic salmon populations in New England have declined precipitously, despite the large-scale introduction of locally derived hatchery fish (Moring et al., 1995). Similarly, between 1905 and 1934, the government of British Columbia released 7.5 million juvenile Atlantic salmon into local waters, primarily on the east coast of Vancouver Island and the lower Fraser River in Canada (MacCrimmon and Gots, 1979; Alverson and Ruggerone, 1997). Neither release was successful in establishing Atlantic salmon populations in the Province, although Carl et al. (1959) stated some natural reproduction may have occurred. Emery (1985) noted that attempts to re-establish Atlantic salmon populations had not been successful even in historic Atlantic salmon habitat, such as the lower Great Lakes, where Brown (1975) stated that introduced Pacific salmonids had successfully established self-reproducing populations.

Lever (1996) noted that, worldwide, no self-sustaining populations of anadromous Atlantic salmon have been established outside its natural range, although landlocked populations were reportedly established in the mountains of Argentina and New Zealand. Reproduction by Atlantic salmon was also observed subsequent to introduction in Chile and Australia, but these transfers also failed to create self-sustaining populations (Waknitz et al., 2002).

The failure of early introductions of Atlantic salmon to produce self-sustaining populations could have been due to the rather primitive hatchery methods used in the early 1900s. However, the same primitive methods that failed to establish Atlantic salmon anywhere in North America proved to be successful in establishing European brown trout, brook trout, and rainbow trout almost everywhere in the earliest days of fish culture, and usually on the first attempt. With these particular salmonids, the success or failure of introduction appears to be associated with attributes inherent to the species, not from the hatchery methods employed. According to Wydoski and Whitney (1979), Atlantic salmon, Arctic char, and Masu salmon are the only non-native salmonids which have not been introduced successfully into the inland waters of Washington State.

The initial transfer of Atlantic salmon to Washington occurred in 1904, according to MacCrimmon and Gots (1979), and Coleman and Rasch (1981) noted that attempts to introduce runs of this species continued until about 1980. Occasional releases of Atlantic salmon into high mountain lakes have also been made since then (Amos and Appleby, 1999). Sea-run and landlocked strains were used, but neither life history form succeeded in establishing self-perpetuating populations. Attempts to establish Atlantic salmon in British Columbia took place during this same period and with similar results, although successful spawning may have occurred in the Cowichan River, Canada, as specimens thought to have resulted from the planting of Atlantic salmon were taken until May 1926, according to Dymond (1932), and repeated by Carl et al. (1959) and Hart (1973). In the last decade, the Atlantic Salmon Watch Program (ASWP) of the DFO in Canada has been reporting catches and sightings of individuals in a long-term study to monitor any establishment of self-sustaining populations, but so far without results (ASWP, 1993 et seq.). Volpe et al. (2000) recently reported that Atlantic salmon had successfully produced offspring in British Columbia.

Several Atlantic salmon farmers in Washington rear juveniles in the Chehalis River basin prior to transfer to seawater in Puget Sound. Since the mid-1980s, escaped Atlantic salmon smolts have been captured in traps designed to monitor the outmigration of juvenile Pacific salmon (Seiler et al., 1995; Amos and Appleby, 1999). However, as of 1998, no returning adult Atlantic salmon have been encountered at adult salmon traps on several tributaries of the Chehalis River system, or caught in tribal gillnet fisheries, which harvest about 10% of all upstream migrants in the main stem of the Chehalis River (D. Seiler, Washington Department of Fish and Wildlife (WDFW), personal communication).

The risk of anadromous Atlantic salmon establishing self-perpetuating populations anywhere outside of their home range is extremely remote, given that hundreds of attempts throughout the last century have not produced one successful self-reproducing population anywhere. Consequently, Atlantic salmon introductions in the Pacific Northwest have never succeeded, even though a few naturally produced juveniles may have been observed from time to time, according to Dill and Cordone (1997).

2.4. Interactions of wild salmon and transgenic fish

As with other agricultural sectors, there is considerable interest within the fish farming sector to improve growth or survival of fish or shellfish through genomic manipulations. In recent years the role of transgenics (descendants of genetically engineered parents whereby introduced DNA has been incorporated and inherited) in traditional farming has been a controversial topic.

The potential exists that transgenic fish, should they escape from fish farms, may reproduce successfully with wild or other transgenic fish and produce offspring which may eventually adapt to their local environments. This is a topic which will receive considerable attention in the future. However, there is no evidence in the literature that transgenic fish have been raised or are currently being raised in Puget Sound waters, and there are no plans to raise them in the future.

3. Epidemics and the transmission of waterborne disease

3.1. Disease of salmonids

Freshwater salmonid diseases observed in Pacific salmon hatcheries in the Pacific Northwest include the bacteria-caused diseases furunculosis, bacterial gill disease, bacterial kidney disease, botulism, enteric redmouth disease, cold water disease, and columnaris, as well as the viral diseases infectious hematopoietic necrosis, infectious pancreatic necrosis, viral hemorrhagic septicemia, and erythrocytic inclusion body syndrome. They also include a large number of parasitic infections, such as gyrodactylus, nanophyetus, costia, trichodina, ceratomyxosis, proliferative kidney disease, whirling disease, and ichthyophonis. All these diseases are described in works by inter alia, Wood (1979), Leitritz and Lewis (1980), Foott and Walker (1992) and Kent and Poppe (1998).

The frequency of occurrence of these pathogens in hatcheries appears to vary geographically. For example, fish health status reports by the Pacific Northwest Fish Health Protection Committee (PNWFHPC, 1988 et seq.) revealed a greater percentage of hatcheries in Alaska testing positive for infectious hematopoietic necrosis, viral hemorrhagic septicemia, furunculosis, and ceratomyxosis than hatcheries located elsewhere in the western states. Conversely, these same hatcheries in Alaska tested positive at the lowest rate for several other salmonid pathogens (Table 1).

In the Pacific Northwest, hatchery diseases associated with freshwater organism can also occur in natural sea water environments after salmon are released from hatcheries or transferred to net-pens for further rearing. Some pathogens, such as *Vibrio anguillarum*, and various parasites are unique to the

Table 1
Facilities (%) testing positive for various salmonid pathogens, July 1988–June 1993 (data from PNWFHPC, 1988 et seq.)[a]

State or agency	IHN	IPN	VHS	EIBS	BKD	FUR	ERM	CWD	PKD	MC	CS	ICH
AK	47.3	0.0	1.2	0.0	75.2	42.5	10.9	27.5	NS[b]	NS	50.0	0.0
CA	24.2	0.0	0.0	0.0	31.2	2.2	23.0	19.4	27.9	12.0	12.8	56.3
ID	20.2	8.7	0.0	15.5	48.4	1.8	12.3	23.6	4.3	15.6	20.4	20.7
MT	0.0	0.0	0.0	0.0	5.6	2.5	0.8	4.2	7.7	0.0	0.0	0.0
OR	18.1	0.3	0.0	24.6	53.1	35.9	17.8	84.8	0.0	2.9	33.3	26.2
WA	11.5	0.7	0.1	34.2	52.6	20.1	17.0	60.3	3.5	0.0	11.9	24.4
USFWS	37.5	1.0	0.0	27.2	84.9	23.7	20.0	34.9	0.0	0.6	30.6	24.0
NWIFC	2.9	0.0	0.6	NS	51.5	14.0	18.1	39.9	56.3	0.0	0.0	15.0
Average	20.2	1.3	0.2	14.5	50.3	17.8	15.0	36.8	12.5	4.4	18.8	20.8

[a] Key: (a) viral diseases: IHN: infectious hematopoietic necrosis; IPN: infectious pancreatic necrosis; VHS: viral hemorrhagic septicemia; EIBS: erythrocytic inclusion body syndrome. (b) Bacterial diseases: BKD: bacterial kidney disease; FUR: furunculosis; ERM: enteric redmouth disease; CWD: coldwater disease. (c) Parasites: PKD: proliferative kidney disease; MC: whirling disease; CS: ceratomyxa; ICH: ichthyopthirius.

[b] Not surveyed.

marine environment, and are normally encountered by wild and hatchery-reared salmonids only after they leave rivers for the sea. Salmonid diseases observed in salmon and trout reared in public and private net-pens in sea water in the Pacific Northwest include vibriosis, furunculosis, bacterial kidney disease, enteric redmouth disease, myxobacterial disease, infectious hematopoietic necrosis, infectious pancreatic necrosis, viral hemorrhagic septicemia, erythrocytic inclusion body syndrome, rosette agent, and a large number of parasitic infections. Infections currently observed in salmonids in marine waters have been listed and described most recently by Kent and Poppe (1998).

Salmon, like any other animals, can carry pathogenic organisms without themselves being infected. For example, numerous bacterial species were observed in tissues of chinook salmon which had returned from the ocean to a hatchery in the lower Columbia River Basin, although the fish displayed no clinical signs of disease (Sauter et al., 1987). Among bacteria observed were *Listeria* sp., *Aeromonas hydrophila*, *Enterobacter agglomerans*, *E. cloacae*, *Staphylococcus aureus*, *Pseudomonas* sp., *Pasteurella* sp., *V. parahaemolyticus*, *V. extorquens*, *V. fluvialis*, *Hafnia alvei*, and *Serratia liquefaciens*.

3.2. *Infectious disease therapy*

Fish diseases and subsequent antibiotic therapy have been normal occurrences at state, federal, and tribal Pacific salmon hatcheries since the 1940s. The status of any disease is monitored and reported annually by the (PNWFHPC, 1988 et seq.). An examination of these disease histories of 45 Pacific salmon hatcheries in the Puget Sound area during the 1980s showed that, on average, each hatchery commonly experienced disease outbreaks from about four different pathogenic organisms, and frequently on an annual basis.

Cumulatively, salmon hatcheries in the Pacific Northwest (Alaska, Washington, Oregon, and Idaho), including those located in Puget Sound, experience hundreds of disease outbreaks every year. For example, the augmented fish health monitoring reports by the Bonneville Power Administration (BPA, 1989 et seq.) revealed that the Cowlitz Hatchery experienced 11 different outbreaks of *Costia* sp. infection between 1983 and 1986, together with bacterial hemorrhagic septicemia (four), cold water disease (nine), bacterial kidney disease (eight), and furunculosis (one). Disease outbreaks have been observed in hatchery salmon reared in saltwater in Washington since the first attempts at seawater rearing in the 1950s, however, the occurrence of fish diseases and their treatment with chemotherapeutics at public hatcheries has not been show to have deleterious effects on wild salmonids.

Diseases in public trout and salmon hatcheries (Table 1) are normally treated with a variety of antibiotics and chemical baths, including oxytetracycline, ®Romet-30, formalin, and iodophores. Drug therapy in federal, state, and tribal hatcheries in Washington State is conducted in line with Federal Drug Administration guidelines (K. Amos, WDFW, personal communication). Antibiotic-resistant strains of bacterial fish pathogens have been observed in Pacific salmon hatcheries in the Pacific Northwest for over 40 years, but no adverse impacts on wild salmonids have been reported as a result of drug use or the occasional development of antibiotic-resistant bacteria.

Schnick (1992) reported that only three therapeutants (formalin, oxytetracycline, and ®Romet-30) and one anesthetic (MS-222) were currently approved by the federal government for use with food fish in public and private artificial propagation facilities. However, the use of antibiotics in the United States is far more restrictive than in other countries. For example, Weston et al. (1994) stated that 26 different antibacterials were approved for use in Japan. This compares currently with three in Canada, according to EAO (1997), and two in the United States (Schnick, 1992).

As Pacific salmon hatcheries rear thousands of metric tons of fish each year, the amount of medicated feed used to treat bacterial salmon diseases is significant. BPA fish health reports (1989 et seq.) estimated that Washington State hatcheries located in the Columbia River Basin used annually about 200 mt of feed containing antibiotics. As these hatcheries number only about 25% of all salmon and trout hatcheries in the State at that time (Myers et al., 1998), but allowing for differing hatchery capacities, a reasonable extrapolation of the total amount of medicated feed used by the public hatchery system in the state in 1990 would have been about 450 mt.

Actual or estimated amounts of medicated feed used annually in private fish culture of Atlantic salmon in seawater and rainbow trout in freshwater are not available at this time for the United States. However, the amount of drugs used elsewhere in salmon farming has greatly declined, mostly as a result of improved husbandry practices, including development of effective vaccines. Willoughby (1999) stated that the historic use of antibiotics by salmon farmers in Norway fell from almost 50 mt in 1987 to less than 700 kg by 1998, and at the same time production increased from 50,000 to 400,000 mt. Currently, the use of active substance is about 600 kg for 450,000 mt production, or 0.00131 mg/kg, a ratio which makes salmon farming the world's largest protein-producing sector with the smallest use of antibiotics (R. Thorarinsson, Alpharma, personal communication). A similar pattern of reduced drug use has occurred in British Columbia and Washington, where total production is only about 10% of that in Norway.

3.3. Disease interactions between wild and propagated salmonids

Documented examples of pathogen transmission between wild and artificially propagated fish are not common, yet have been known to occur (Brackett, 1991). For example, the planting of infected Atlantic salmon smolts from Norwegian federal salmon hatcheries into rivers in Norway was responsible for the introduction of the freshwater parasite *Gyrodactylus salaris*, which caused the extirpation of Atlantic salmon in many river systems (Johnsen and Jensen, 1988). The salmonid viral pathogen IHN (infectious hematopoietic necrosis) was introduced to Japan from a shipment of infected sockeye salmon eggs from a hatchery in Alaska, and subsequently caused epizootic mortality in Japanese chum salmon and in two species of landlocked salmon which occur only in Japan (McDaniel et al., 1994). In these two cases, the indigenous salmonids in Norway and Japan were exposed to novel pathogens to which they had little or no immunity. In Washington the pathogens found in cultured salmonids are identical to those known to occur in wild salmon (Amos and Appleby, 1999).

The possibility that local Atlantic salmon stocks are more likely to carry pathogens than hatchery stocks of Pacific salmon is not supported by the scientific literature. Salmonids, including Atlantic salmon, can only carry diseases to which they have been exposed. The New England Atlantic salmon stocks used by Washington growers were certified by federal pathologists to be pathogen-free prior to shipment from east coast hatcheries between 1980 and 1986, inclusive, and have been reared exclusively in the Pacific Northwest for many generations (Waknitz et al., 2002). Their diseases, if any, would be no different than the diseases found in nearby Pacific salmon hatcheries. In addition, Washington regulations require that all broodstocks of hatchery salmon, including Atlantic salmon broodstocks, are examined for pathogens each year. None of these annual screenings has recorded any incidence of a non-indigenous salmon disease being transmitted into the Pacific Northwest by North American stocks of Atlantic salmon.

Table 2
Number (in millions) of salmon released or escaped by species and location along the west coast of North America, 1980–1995 (data from ASWP, 1993 et seq.; NRC, 1995–1996; Mahnken et al., 1998)

State or region	Atlantic	Sockeye	Chum	Steelhead	Pink	Coho	Chinook
Alaska	0	978	3885	2	8610	193	98
British Columbia	~0.4	3930	2870	17	533	300	721
Pacific Northwest	~0.6	52	1081	359	21	726	4320
Total	~1.0	4960	7836	377	9164	2219	5139
Total (%)	0.0003	16.7	26.4	1.2	30.9	7.5	17.3

Pacific salmonids do not seem to be put to any increased risk of pathogen transmission when exposed to water in which Atlantic salmon have been reared. For example, Rocky Ford Creek, near Ephrata in eastern Washington, is considered one of the premier trout streams in the state but its entire flow consists of effluent from an Atlantic salmon hatchery (J. Parsons, Troutlodge Inc., personal communication). There are no reports of diseased trout in this stream in either the scientific literature or the popular fishing press.

3.4. The scale of artificial propagation

Because of the enormous numbers of hatchery-reared salmonids released into rivers and lakes in the Pacific Northwest over many months, the potential for transmission of disease to wild stocks from hatchery-reared Pacific salmon and trout greatly exceeds that of farmed Atlantic salmon and rainbow trout which escape. This is because accidental escapes constitute an insignificant percentage of all artificially propagated salmon which end up in natural waters in the area. However, no adverse impacts on wild salmonids by hatchery-reared Pacific salmon entering marine waters each year have been recorded in the scientific literature.

Atlantic salmon are propagated in only a few facilities in the Pacific Northwest, compared with several hundred federal, state, tribal, and cooperative hatcheries which rear Pacific salmon and trout. The primary difference in the disease incidence between artificially propagated Atlantic and Pacific salmon is one of scale. Mahnken et al. (1998) reported that, since 1980, the number of Pacific salmon released from all west coast public and tribal hatcheries was about two billion fish annually. This number is 4 or 5 orders of magnitude larger than the number of Atlantic salmon which may have escaped from private net-pens since 1980 (Table 2).

Furthermore, some public hatchery programs also retain their juveniles in salt-water net-pens for some time before release. By comparing only the number of Pacific salmon released from these net-pens, the magnitude and geographic distribution of these artificially propagated Pacific salmon is still much greater than the number and magnitude of Atlantic salmon reared in farms. For example, NRC (1995–1996) reported that coho salmon were released annually from 18 different marine net-pen sites in Puget Sound, chinook salmon from 13 different sites, and chum salmon from 10 different sites. The annual release from these marine sites between 1980 and 1992 averaged about 10 million fish. These fish had sometimes been exposed to various salmonid pathogens while in seawater, including the causal agents of bacterial kidney disease, vibriosis, and furunculosis. Infections in these fish were often treated with antibiotics prior to their release (PNWFHPC, 1988 et seq.).

3.5. Disease control policies in Washington and the United States

In Washington State, all public and private growers of salmon, including Atlantic salmon hatchery operators, are required to adhere to strict disease control polices which regulate all phases of fish culture, from egg take to harvest and/or release. Each year at spawning time, adult salmon at public and private hatcheries must be sampled for viral, bacterial, and parasitic organisms. If any of several reportable organisms are detected in fish at a hatchery, or have been detected within the past 5 years, transfer of eggs or fish from that facility is prohibited.

The movement of fish and eggs across state or international borders is regulated by the US Fish and Wildlife Service, which has stipulations and controls in accord with state regulations. For the case in point, all Atlantic salmon stocks distributed to local growers by NMFS were federally certified by federal pathologists before transfer from New England, and have been annually certified since then under Washington guidelines and procedures.

Most of the cumulative body of information pertaining to salmon farming developed in the last several decades has already been integrated into the regulatory processes of Washington State. This scientific information has been incorporated into state regulations relating to farm fish escapes, antibiotic residues in sediments, accumulation of organic wastes on the seabed, importation of non-native and non-local species, and disease management. These and other important regulations and documents pertaining to private salmon farming have been described and discussed by Elston (1997) and Amos and Appleby (1999), and include:

- Final programmatic EIS for fish culture in floating net-pens.
- Recommended interim guidelines for the management of salmon net-pen culture in Puget Sound.
- Environmental effects of floating mariculture in Puget Sound.
- Environment fate and effects of aquacultural antibacterials in Puget Sound.
- Disease control policies of Washington.
- Disease control policies of the United States.
- Fish health manual of the Washington Department of Fish and Wildlife.

4. Potential ecological impacts of Atlantic salmon

In areas where Atlantic salmon are indigenous, such as Scandinavia, Great Britain, and eastern North America, adverse genetic and ecological impacts for natural populations of Atlantic salmon have been reported by, inter alia, Hearn and Kynard (1986), Beall et al. (1989), Heggberget et al. (1993), Jones and Stanfield (1993), and Gross (1998), following programmed releases or escapes of artificially propagated Atlantic salmon from public hatcheries and private net-pens. The impacts included reduction in genetic adaptation and capacity to evolve in wild Atlantic salmon resulting from interbreeding with artificially propagated Atlantic salmon, and competition for food and space between wild and hatchery stocks of Atlantic salmon.

These adverse effects occurred because both the artificially propagated and wild salmonid species were Atlantic salmon. Escaped Atlantic salmon on the Pacific coast of North America do not have congeneric wild individuals with which to interact. Hence, in the Pacific Northwest region it is the programmed releases of hatchery stocks of Pacific salmon which have the potential to produce impacts on wild Pacific salmon comparable to those found between propagated and wild Atlantic salmon in Europe and eastern North America (Waknitz et al., 2002).

Adverse genetic and/or ecological interactions on local wild salmon populations resulting from plants of artificially propagated Pacific salmonids have been well-documented in the Pacific Northwest in papers by Campton and Johnston (1985), Nickelson et al. (1986), Behnke (1992), Kostow (1995), and Leider et al. (1987). Similarly, documents by public agencies in Canada (ASWP, 1993 et seq.) and Washington (Amos and Appleby, 1999) have revealed no detrimental effects in the region which can be related to deliberate or accidental introductions of Atlantic salmon.

4.1. Social interactions between Pacific and Atlantic salmon

In laboratory studies in New England, Gibson (1981) reported that introduced Pacific steelhead juveniles were more aggressive than Atlantic salmon. In turn, Atlantic salmon fry appeared to be more aggressive than coho salmon fry when introduced into open pools, although it was recognized that open pools are not the preferred habitat of coho salmon fry. Beall et al. (1989), in a similar experiment, reported that the survival of Atlantic salmon was reduced in the presence of older coho salmon fry.

In trials of inter-specific combative behavior in New England, Hearn and Kynard (1986) observed that rainbow trout juveniles initiated three to four times more aggressive encounters than did Atlantic salmon, and concluded that it would take very large numbers of Atlantic salmon juveniles to displace or even disrupt native species. Jones and Stanfield (1993), in a study conducted in a Lake Ontario tributary once inhabited by Atlantic salmon, reported that their attempts to reintroduce hatchery strains of Atlantic salmon were significantly impaired in the presence of naturalized Pacific salmon juveniles, compared with reintroduction in stream sections where Pacific salmon juveniles had been removed.

4.2. Predation by Atlantic salmon

In a study on predation by caged fish in British Columbia by Black et al. (1992), stomach analyses revealed that <1% of coho and chinook salmon in net-pens contained the remains of fish. Since 1992, scientists of the Canadian federal government at Nanaimo have examined the stomach contents of escaped Atlantic salmon recovered in the open waters of British Columbia. Fish remains of any sort were rarely observed, and no confirmed salmonid remains have been reported (ASWP, 1993 et seq.). This confirms earlier work by Tynan (1981) who examined the stomachs of 93 coho salmon captured after release from a net-pen near Squaxin Island, in South Puget Sound, and reported that only three stomachs contained remains of fish, all identified as smelt.

At the NMFS Manchester Research Station in Puget Sound many species of forage fish have been observed seeking refuge from predators in net-pens containing large Atlantic salmon. Among the species observed are known prey of salmonids, such as herring, smelt, candlefish, shiner perch, and tube snouts. These prey species enter the net-pens voluntarily and then grow too large to exit. Alverson and Ruggerone (1997) noted that many thousands of these small fish had been observed in Atlantic salmon net-pens, and had to be removed by hand.

Another line of evidence also leads to the conclusion that farmed salmon eat little natural forage. Deardorff and Kent (1989) observed that the flesh of farmed Atlantic, chinook, and coho salmon reared in net-pens in Puget Sound were free from larval *Anisakis simplex*, a fish-borne parasite known to infect humans. They also observed that the flesh of all wild-caught sockeye salmon contained this human parasite. Since this particular parasite is transmitted via the food chain, the fact that farmed salmon had none of these parasites demonstrates that they were not participating in the natural food web, and that the consumption of pasteurized commercial diets afforded farmed salmon less opportunity to become infected with nematodes and other helminths (Deardorff and Kent, 1989). Similar findings were observed in Europe. Wild, free-ranging European Atlantic salmon all contained anisakid larvae, while no European Atlantic salmon reared in net-pens were infested with this intestinal parasite (Angot and Brasseur, 1993).

Buckley (1999) showed that cannibalism and predation on other salmonids by chinook salmon when feeding was uncommon in Puget Sound waters. It is therefore unlikely that escaped Atlantic salmon, conditioned to a diet of artificial feed pellets and trained to be fed by humans, could have greater predation impacts on juvenile native salmonids than the low impact observed with free-swimming Puget Sound chinook salmon.

In the Cowichan River in British Columbia, non-native brown trout became established soon after its first introduction in 1932. Idyll (1942) observed that native salmon and trout, and their eggs, were a significant dietary component of newly established Cowichan River brown trout, and were the primary food item of large brown trout. Recent evaluations by Wightman et al. (1998), of steelhead populations on the east coast of Vancouver Island, showed that the Cowichan River was one of only two rivers (out of 27 evaluated) with a relatively healthy steelhead population. Therefore the successful colonization of the Cowichan River by a highly piscivorous species such as the brown trout has apparently had no adverse impact on steelhead abundance for more than 60 years, whereas concurrent attempts to establish Atlantic salmon in the Cowichan River basin were failures.

5. A comparison of potential impacts of propagated Pacific salmon

Adverse genetic and ecological effects from artificially propagated Pacific salmon have been documented in a number of Biological Status Reviews of Pacific salmonids published by NMFS in fulfillment of their responsibilities under the Endangered Species Act (ESA). The reviews contain information from the scientific literature which document known adverse ecological impacts sometimes associated with the artificial propagation and release of Pacific salmon. In recent years, west coast management agencies have eliminated many of the policies which contributed to these adverse effects. However, examining some of the known adverse impacts of Pacific salmon hatchery programs offers an effective demonstration that the ecological and genetic risks associated with Atlantic salmon farming are small in the waters of Puget Sound. The following paragraphs provide a brief review by species of adverse effects of artificial propagation which occurred under the old Pacific salmon hatchery policies.

5.1. Steelhead trout

Hatchery stocks of steelhead have been widely distributed. Few native steelhead stocks exist in the contiguous United States which have not had some influence from hatchery operations. For example, Busby et al. (1996) cite the summer steelhead program at the Nimbus Hatchery in Central Valley, California, was established with fish from a distant coastal tributary hatchery which was itself earlier established with lower Columbia River summer steelhead.

Howell et al. (1985) reported that over 90% of the 'wild' steelhead spawning in the Cowlitz River, Washington, originated in a hatchery, and some of these fish exhibited genetic characteristics of Puget Sound steelhead due to previous transfers of Puget Sound stock to the Cowlitz Hatchery.

Chilcote (1997) reported that, since 1980, the percentage of non-native stray hatchery steelhead (from upper Columbia River and Snake River hatcheries) spawning in the Deschutes River had increased to over 70% of the run, while the percentage of native, wild steelhead spawning in the Deschutes River in Oregon decreased to less than 15%. Phelps et al. (1997) postulated that introductions of non-native steelhead stocks in Washington, primarily Chambers Creek winter steelhead and Wells and Skamania summer steelhead, may have changed the genetic characteristics of some populations sufficiently so that the original genetic relationships between stocks may have been obscured. Finally, Leider et al. (1987) concluded that the genetic fitness of the wild Kalama River population in Washington had been compromised by maladaptive gene flow from excess hatchery escapement.

5.2. Chinook salmon

About 2 billion hatchery chinook salmon have been released into Puget Sound since 1953, with fish from the Green River Hatchery being the dominant stock since 1907. Concerns that this strategy may erode genetic diversity was raised by Myers et al. (1998). As recently as 1995, 20 hatcheries and 10 marine net-pen sites throughout Puget Sound regularly released Green River-stock chinook salmon. Busack and Marshall (1995) reported that the extensive use of this stock had an undoubted impact on among-stock diversity within the South Puget Sound, Hood Canal, and Snohomish summer/fall genetic diversity unit (GDU), and may also have impacted GDUs elsewhere in Puget Sound and the Strait of Juan de Fuca.

Chinook salmon from the Rogue River in Oregon were recently released on the Oregon side of the Lower Columbia River to produce a south-migrating stock to avoid interception in commercial fisheries in British Columbia and Southeast Alaska. However, chinook salmon exhibiting Rogue River fall chinook salmon genetic markers were subsequently observed by Marshall (1997) in several lower Columbia River tributaries, and were estimated to comprise about 13% of the Lower Columbia River naturally produced chinook salmon sampled in 1995. Marshall et al. (1995) had earlier stated that most of the naturally spawning spring chinook salmon in Lower Columbia River tributaries were hatchery strays. Adverse impacts resulting from the introduction of artificially propagated fish into native populations of chinook salmon were identified as a primary concern by NMFS in the status of west coast chinook salmon populations (Myers et al., 1998).

5.3. Chum salmon

Johnson et al. (1997) reported that five hatchery stocks and several wild populations of chum salmon outside the Hood Canal, which received eggs from Hood Canal hatcheries for several years, exhibited genetic frequencies more similar to those in Hood Canal hatchery populations than to populations in nearby streams not receiving Hood Canal hatchery stocks. Their analyses of gene frequency patterns were consistent with the hypothesis that egg transfers between hatcheries and out-plantings of Hood Canal stock fry had genetically influenced the receiving populations. According to Phelps et al. (1995) such transfers were terminated because of the potential jeopardy to wild gene pools through interbreeding.

5.4. Coho salmon

Weitkamp et al. (1995) noted it was not possible to identify any remaining natural populations of coho salmon in the lower Columbia River below Bonneville Dam, due in large part to persistent and extensive hatchery programs. In a recent survey of coho salmon spawning habitat in the lower Columbia River, NRC (1999) estimated that about 97% of recovered spawned-out carcasses originated from hatchery releases. Hatchery fish were observed in high percentages in streams up to 45 miles from the nearest hatchery. In many streams, wild, native coho salmon were not observed at all. In a similar survey in Hood Canal, NRC (1997) estimated over 50% of all spawning coho in streams within a 10-mile radius of a net-pen release site were the juveniles released from the pen 18 months earlier.

Kostow (1995) stated that hatchery programs in Oregon may have contributed to the decline of wild coho salmon by supporting harvest rates in mixed-stock fisheries which were excessive for sustained wild fish production, and by reducing the fitness of wild populations through interbreeding of hatchery and wild fish. Furthermore, they may have reduced survival of wild coho salmon juveniles in Oregon through increased competition for food in streams and estuaries, through attraction of predators during mass migrations, and through initiation of disease problems.

Weitkamp et al. (1995) also reported that artificial propagation of coho salmon had appeared to have substantial impact on native coho salmon populations to the point where it was difficult for NMFS to identify self-sustaining native stocks in Puget Sound, as over half the returning spawners originated in hatcheries. Spawn-timing had been advanced by selective breeding so that most hatcheries met their quotas for eggs by early November, and fish arriving at the hatchery with the later run (which would be coincidental with the spawn-time of the wild or native fish) were not propagated. As a result of such practices, according to Flagg et al. (1995), segments of hatchery coho salmon populations which historically returned as late as January–March have disappeared from many river systems, resulting in a significant loss of life history diversity.

5.5. Trouts

Long-term introductions of rainbow trout into western streams originally inhabited only by cutthroat trout have resulted in widespread extinctions of native cutthroat trout through introgressive hybridization, according to Leary et al. (1995). They noted that hybridization between introduced brook trout and bull trout is far-reaching in the western United States, and usually produces sterile hybrids. Behnke (1992) noted that introduced brown trout had commonly replaced interior subspecies of cutthroat trout in large streams throughout the same region, and introduced brook trout were the most common trout to be found in many small streams.

The situation regarding attempts to establish Atlantic salmon populations is much different. In summary, MacCrimmon and Gots (1979) described frequent attempts and failures to introduce Atlantic salmon to the western states, many of which occurred in the same river systems and at the same time as the salmonid introductions listed above. Since then no recent introductions, accidental or not, have succeeded.

6. A comparison of impacts of other non-indigenous fish species

As many as 50 species of non-native fish are successfully established in the western United States (Table 3). The Atlantic salmon is not one of those listed. Some adverse impacts associated with the establishment of these species are discussed below. None of these negative impacts has been associated with the artificial propagation of Atlantic salmon in the Pacific Northwest.

ODFW/NMFS (1998) documented many introductions of non-native species which proved to be harmful to native salmon. For example, walleye, bass, perch, sunfish, brown trout, and brook trout, among others, are all now well-established in Pacific Northwest waters and are well-known predators and/or competitors of native salmon and trout. Beamesderfer and Nigro

Table 3
Status of non-native fish introductions in the Pacific Northwest vis-à-vis their behavior relative to Pacific salmonids (data after Behnke, 1992; WDFW, 1993; Lever, 1996; Dill and Cordone, 1997; ODFW/NMFS, 1998)

Non-native species	Naturalized in Washington	Naturalized in Oregon	Naturalized in California	Predator	Competitor	Hybridize
Atlantic salmon						
Non-native rainbow	X	X	X	X	X	X
Non-native cutthroat	X	X	X	X	X	X
Lahotan cutthroat	X					X
Westslope cutthroat	X		X		X	X
Brown trout	X	X	X	X	X	X
Brook trout	X	X	X	X	X	X
Lake trout	X	X	X	X		X
American shad	X	X	X		X	
Threadfin shad			X			
Lake whitefish	X					
Arctic grayling	X		X			
Grass pickerel	X			X		
Northern pike	X		X	X		
Striped bass		X	X	X		
White bass			X			
Common carp	X	X	X		X	
Grass carp	X		X			
Tench	X		X			
Brown bullhead	X	X	X	X	X	
Black bullhead	X	X	X	X	X	
Yellow bullhead	X	X	X	X	X	
Flathead catfish	X		X	X	X	
Blue catfish	X			X	X	
Channel catfish	X	X	X	X	X	
White catfish		X	X	X	X	
Largemouth bass	X	X	X	X	X	
Smallmouth bass	X	X	X	X	X	
Warmouth bass	X	X	X	X	X	
Rock bass	X			X	X	
Redeye bass			X			
Northern spotted bass			X			
Alabama spotted bass			X			
Black crappie	X	X	X	X	X	
White crappie	X	X	X	X	X	
Green sunfish	X	X	X	X	X	
Bluegill	X	X	X	X	X	
Pumpkinseed	X	X	X	X	X	
Redear sunfish			X			
Bigscale logperch			X			
Yellow perch	X	X	X	X	X	
Walleye	X	X	X	X	X	

(1988) and Beamesderfer and Ward (1994) estimated that walleye and smallmouth bass introduced into the John Day Reservoir of the Columbia River consumed an average of 400,000 and 230,000 juvenile salmonids, respectively, each year.

Daily et al. (1999) reported that juvenile salmonids from seven ESUs currently listed as threatened or endangered under ESA must migrate through the John Day Reservoir; and in some coastal lakes in Oregon the summer rearing of coho salmon fry no longer occurred due to predation by introduced largemouth bass. Seiler (WDFW, personal communication) has observed that introduced bass eat out-migrating salmon, including juvenile chinook salmon, as they pass through the Lake Washington Ship Canal in Seattle.

In 1997 and 1999, in response to the escape of some net-pen Atlantic salmon, WDFW suspended fishing regulations concerning size and bag limits for these fish. Licensed anglers fishing in open management zones were permitted to keep all Atlantic salmon they could catch, of whatever size. Suspension of fishing regulations for an introduced, non-native species in waters inhabited by native salmonids at some period of their life cycle is a management strategy which WDFW has used before. For example, freshwater angling regulations for non-native brook trout in Washington were recently relaxed to increase harvest of this species, and regulations for non-native shad, perch, crappie, and carp have long-since been dismissed entirely.

Catch limits and close seasons for non-native salmonids in Washington (such as brown trout, golden trout, lake trout, landlocked Atlantic salmon, California-strain rainbow trout, and grayling) have given these species many of the same protections given to native salmonids. Furthermore, several non-native species known to prey on salmonid juveniles (such as smallmouth and largemouth bass, walleye, and channel catfish) are currently managed for sustained natural reproduction through state fishing regulations which limit the take of large individuals which have the greatest reproductive potential. From a review of the literature, Atlantic salmon have far less potential for adverse impacts than all the non-native species noted above. Therefore, if there is a goal to decrease unnecessary adverse impacts on listed native salmonids by non-indigenous fish, it would not be an inconsistent strategy for states in the Pacific Northwest to suspend regulations for the harvest of all non-indigenous fish by licensed anglers.

7. A perspective of Pacific salmon culture in northwest waters

Most of the concerns for the negative impacts of Atlantic salmon on native salmon in the Pacific Northwest are hypothetical. They are associated with the belief that artificially propagated fish are bigger, stronger, and more vigorous than wild fish. Although this opinion has been generally disproved in a multitude of studies, many studies and reviews, among them WDFW (1993) and the NMFS Status Reviews, have shown that adverse impacts from hatchery stocks of Pacific salmon are likely to occur if and when hatchery fish comprise a large portion of the total population. Therefore, it is instructive to compare the numbers of artificially propagated Pacific salmon released each with the number of Atlantic salmon estimated to escape each year to give a perspective as to where and when the greatest risks actually occur, and to what degree, keeping in mind recent changes in hatcheries strategies in the Pacific Northwest which will likely reduce the impact of hatchery fish on wild fish.

Mahnken et al. (1998) reported that several billion Pacific salmon were released from freshwater hatcheries and marine net-pens in North America each year (see Table 2). Although Washington, Oregon, Idaho, and California had more salmon hatcheries, the total number of fish released in the contiguous states of the Pacific Northwest was dwarfed by the vast number of hatchery salmon released in Alaska each year. Statistics documented by ADF&G each year show that about 1.4 billion hatchery salmon have been released into natural rearing areas since 1996 (ADF&G, 1997 et seq.), and 13.5 billion into all Alaskan waters since 1990.

Pacific salmon have been released from hatcheries with the understanding that they must compete for food and habitat in common with native wild salmon to survive. Until recently the capacity of the ocean pastures were thought to be limitless. Recent investigations by Heard (1998), Cooney and Brodeur (1998), and Beamish et al. (2000) show that food availability in the ocean fluctuated over time and might be limiting salmon abundance. Bisbal and McConnaha (1998) proposed that fishery managers planning to release vast numbers of fish from hatcheries should take these fluctuations into account. Compared with the great numbers of Pacific salmonids released each year into the marine ecosystems, there is no evidence in the literature that the few Atlantic salmon which escape pose any competitive threat to native Pacific salmon for forage or habitat.

The majority of Atlantic salmon escapes have occurred in Puget Sound. However, the number of escapees is extremely low compared with the number of Pacific salmon deliberately introduced into the ecosystem. NRC (1995–1996) documented that the total number of cultured chinook, coho, and chum salmon released into Puget Sound tributaries by various fisheries agencies between 1980 and 1992 exceeded 2.2 billion in number. Although data are not yet available through the year 2000, the number is predictably over 3 billion.

The adverse ecological and genetic interactions associated with abundant releases of hatchery-reared Pacific salmon are well-documented and present a more serious risk for native salmonids. There is no evidence in the literature which associates adverse impacts with the escape of Atlantic salmon in the Pacific Northwest, or that they even pose a serious threat (Waknitz et al., 2002).

NRC (1995) reported that over 240 million small, non-migratory, hatchery coho salmon were released into Puget Sound tributaries between 1980 and 1992, or an annual average of about 18 million. More recently, the Fish Passage Center (FPC) in Portland, Oregon, which collects and collates mark-and-release information, reported that this number has been reduced by over half, with changes in hatchery strategies. Nonetheless, these artificially propagated fish have to survive by competing for natural food and rearing space with native salmon for about 18 months. Using typical wild coho salmon life history data, such as egg-to-fingerling survival levels of 10% and a fecundity of 4000 eggs per female, it would take every year about 92,000 mature, successful Atlantic salmon spawners (1:1 female:male ratio) to produce enough fry to equal the numbers of artificially propagated non-migrant coho salmon planted in Puget Sound rivers every year.

Applying the same calculations on a more local scale, the FPC reported that about 7,500,000 coho salmon fry of hatchery origin were planted in the Green River between 1993 and 1996. To produce an equal number of Atlantic salmon juveniles, it would be necessary for over 9000 mature Atlantic salmon adults to escape and spawn successfully in the Green River each year. However, ASWP (1993 et seq.) data reveal fewer than 20 mature Atlantic salmon in all Washington rivers systems during 1997, although some were not surveyed completely. Best management practices (BMPs) for net-pen salmon farming developed by the British Columbia Salmon Farmers Association and the Washington Fish Growers Associations continue to stress the importance of preventing escapes, but any potential adverse impacts associated with escaped Atlantic salmon cannot begin to approach the potential impacts of fish released from Pacific salmon hatchery programs, even when recent changes in hatchery strategies are considered.

Volpe et al. (2000) recovered less than 100 naturally spawned juvenile Atlantic salmon during counts of salmon juveniles in the Tsitika River in British Columbia, compared with more than 10,000 juvenile Pacific salmonids observed in this river in the same survey. The juvenile Atlantic salmon made up approximately 1% of the juvenile salmonids in the river and presented no competition to native salmonids for food or rearing space. Since 1998, only three suspected naturally produced Atlantic salmon juveniles have been observed in British Columbia rivers, despite a greatly increased level of surveillance by the ASWP (ASWP, 1993 et seq.). No naturally produced Atlantic salmon have been observed in Washington rivers to-date, although surveys have not been as vigorous as those in Canada.

The success of a hatchery or net-pen facility, as well as the degree to which hatchery fish potentially impact wild fish, is largely determined by how well fish survive in the wild after release. Some hatchery programs are very successful at producing fish for harvest. Johnson et al. (1997) noted that hatcheries in Alaska, through extremely successful early rearing strategies, produced prodigious numbers of adult chum and pink salmon, two species which normally have juvenile to adult survival rates of $<0.5\%$. The Hidden Falls Hatchery in Southeast Alaska has consistently experienced survivals of 3–8% with chum salmon (Bachen, 1994), resulting in this single facility producing more than 22% of all the chum salmon, wild and hatchery, caught in the fisheries of southeast Alaska (Johnson et al., 1997). ADF&G (1997 et seq.) record that 93.6% of all pink salmon caught in Prince William Sound in 1997 were artificially propagated and that, for all salmon harvested in common property fisheries throughout Alaska that year, 22% of the coho salmon, 30% of the pink salmon, and 65% of the chum salmon originated in hatcheries. Overall, hatcheries contributed 26% of all salmon harvested in Alaska in 1997. In 2000, 34% of the total salmon catch in Alaska was produced in Alaskan hatcheries. Additional contributions to Alaska's commercial harvest from hatcheries in British Columbia, Washington, Oregon, and Idaho were not included in this analysis. In Washington, it is estimated that hatcheries provide about 75% of all coho and chinook salmon harvested, as well as 88% of all steelhead harvested. As west coast hatcheries put enough artificially propagated salmon into the natural environments to produce a significant proportion of the harvest in Alaska, and the overwhelming proportion of fish harvested in Washington, it is not possible that the relatively inconsequential competition for natural resources from present levels of escaped Atlantic salmon could even be evaluated.

Although escaped Atlantic salmon in western North America are known to consume some natural forage after entering the natural environment, the amount eaten is relatively small. Data from 6 years of observations by ASWP (1993 et seq.) show that about 6% of all escaped Atlantic salmon recovered in the North Pacific contained natural food in their stomachs. Thus, if annual escapes averaged 200,000 fish, and if the 6% which then ate consumed a total of 150 g of food, then the escaped Atlantic salmon will deprive wild Pacific salmon of about 1800 kg of natural forage per year. By comparison, based on a gross ecological efficiency of 20%, 5 kg of natural forage is required to produce 1 kg of salmon. Therefore, the 63 million salmon which returned to hatcheries in Alaska in 2000 at an average weight of 1.8 kg (ADF&G, 1997 et seq.) had deprived the wild populations of 567 million kilogram of natural forage.

Given that it is necessary for millions of hatchery Pacific salmon to compete successfully with wild salmon in natural environments to survive and contribute to the economies of Alaska and Washington, expressions of both professional and public concern regarding competition for food from relatively small numbers of escaped Atlantic salmon appear misdirected. A review of the literature reveals that the potential for artificially propagated Pacific salmon released from public hatcheries to pose adverse impacts with wild Pacific salmon through competition for food is far greater than the potential for competition posed by escaped Atlantic salmon.

8. NMFS Biological Status Reviews of west coast Pacific salmon stocks

Since 1991, 14 Biological Status Reviews have been published by NMFS as part of its federal obligation under ESA. These reviews (see Weitkamp et al., 1995; Busby et al., 1996; Hard et al., 1996; Gustafson et al., 1997; Johnson et al., 1997; Myers et al., 1998; Johnson et al., 1999) are individual scientific studies of the current status of all anadromous salmonid populations on the west coast of the United States. These are generally regarded as the most complete scientific reviews of their kind ever published. They form the basis for NMFS actions concerning ESA listing determinations, as well as the scientific basis for NMFS testimony for litigation and courtroom challenges to proposed and implemented listings under ESA.

In these reviews, experienced federal scientists have identified many factors which have adverse effects on the Pacific salmonids of the west coast. The potential biological impacts of cultured salmon have continuously been identified as a primary factor (see Hard et al., 1992; Waples, 1991). Atlantic salmon farms have not been identified as the cause of any adverse effects in any of the 14 reviews conducted to-date, which cover 58 separate ESUs for Pacific salmon species, or factors in the decline of west coast populations of chinook salmon or steelhead.

9. Summary

Accidents have occurred enabling farmed salmon to escape. Such incidents are likely to continue following some unique meteorological event or human error. The possible negative consequences of such events have been limited in part by implementation of pre-prepared recovery plans, some of which have included deregulating catch limits for public fishing on escaped farm fish, and by programs to monitor the background populations of fish in nearby watersheds. These responses will continue to be effective management practices to minimize impact, together with further advances in the technology. Improvements in the design and engineering of net-pens and their anchorages, and the use of new net materials, are continuing to reduce the incidents of loss following structural failure or damage from large predators.

There is little or no risk that the escape of Atlantic salmon, a non-native species, will impact the ecosystem of the Pacific Northwest. Between 1951 and 1991, the State made 27 releases of 76,000 smolts of Atlantic salmon of various sizes into the Puget Sound Basin in attempts to establish a recreational fishery on the west coast, but without success. A reporting regulation was imposed in 1996, and records since then show that some 600,000 farmed salmon escaped between 1996 and 1999. These were mostly fish between 0.5 and 1.5 kg in weight. Only 2500 of these particular escapees were subsequently accounted for. Many were taken immediately by recreational fishermen angling close to the net-pen farms, and a few others were taken at random by commercial fishermen in Puget Sound and beyond. A few Atlantic salmon (which may have originated in either Washington or British Columbia) have been recovered in commercial fisheries as far away as the Alaskan Peninsula. However, the total number of fish recovered is small. The rest remain unaccounted, but it is generally assumed that the domesticated existence and docile behavior of farm fish makes them easy victims of predators, especially the large populations of marine mammals which now exist throughout the Pacific Northwest.

There is no evidence of adverse genetic impacts associated with escaped Atlantic salmon on the west coast of North America, as they do not have congeneric wild individuals with which to interact. Hybrids between Atlantic salmon and the Pacific salmonid species can be produced in vitro, but with difficulty. Hybrids between Atlantic salmon and brown trout, another non-native species, are more easily produced in vitro, and occur readily in nature. Atlantic salmon × Pacific salmonid hybrids are not observed in nature, whether for introduced Atlantic salmon in North America, or for introduced North American salmonids to Europe and the other continents. By comparison, successful hybridization between some North American salmonids is regularly recorded.

Atlantic salmon are unlikely to colonize salmon habitat in the Pacific Northwest. Accidents occur, and farm fish of various sizes occasionally escape in large numbers. About 1 million Atlantic salmon have escaped from net-pen farms in Puget Sound and British Columbia since 1990. Only a few were accounted for in recreational and commercial fisheries. In addition to escapes, deliberate releases of Atlantic salmon to establish local self-sustaining populations have been made in the Pacific Northwest since the beginning of the century, with the last release in 1991. Although routine monitoring programs occasionally find naturally produced juveniles, naturally produced adults have yet to be observed.

Like all salmonids Atlantic salmon are high on the food chain. But few prey items of any sort have been found in the stomach contents of escaped Atlantic salmon which have been recaptured. As survival in the wild is extremely low for escaped farm fish, it is assumed that their domestic upbringing makes them poor at foraging successfully for themselves. Therefore, the few natural prey items any escaped fish might consume is negligible, especially when compared with the competitive food requirements of the juvenile Pacific salmon deliberately released into Puget Sound and its tributaries from hatcheries.

All salmonids are predators. However, all analyses of the stomachs of recovered farm Atlantic salmon, and of the few naturally produced juveniles caught in the wild, have failed to show evidence of preying on native salmonid species. This is not the case of other introduced non-native species which are known to be voracious predators of juvenile Pacific salmonids. Some of these non-native predators have been deliberately and/or accidentally introduced, and are now managed for sustained natural reproduction to enhance recreational fisheries and for their contribution to sport fishing revenues.

Provided no new stocks or eggs of Atlantic salmon are introduced into the region, farm Atlantic salmon cannot be a vector for the introduction of an exotic pathogen into Washington State. The extensive movement of aquatic animals and plants globally is known to carry the risk of introducing exotic diseases but movement of fish into and within Pacific Northwest states is now well-regulated with the requirement for disease-free certification. No Atlantic salmon stocks have been transferred into the State of Washington since 1991.

The perceived hazards of transgenic farms products, such as human allergies or unnatural competitors in the ecosystem, are hypothetical issues for net-pen salmon farming in Puget Sound. There is no evidence in the literature that transgenic fish have been raised or are being raised in the Pacific Northwest, and there are no plans to raise them.

There is a low risk that Atlantic salmon will increase the incidence of disease among wild fish. The specific diseases and their prevalence in Atlantic salmon stocks cultured in net-pens in Puget Sound are not shown to be any different than those of the more numerous cultured stocks of Pacific salmon in hatcheries, which in turn are not known to have a high risk for infecting wild salmonids. All Pacific and Atlantic salmon stocks currently cultured in Washington are inspected annually for bacterial and viral pathogens, and the movement of fish from place to place is regulated by permit. As escaped Atlantic salmon compromise approximately 0.0003% of all artificially propagated salmon present in the eastern North Pacific Ocean since 1980, it can be assumed that they will have increased the disease risk by that amount.

Acknowledgements

The authors would like to thank Kenneth M. Brooks, William T. Fairgrieve, Conrad V.W. Mahnken, Colin E. Nash, and Michael B. Rust, the other co-authors of this series of papers, who reviewed and commented on this and the other works. The authors also acknowledge the critiques of nine additional reviewers who read the original manuscript (NMFS, 2001). Their suggestions were much appreciated.

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