

On the decline of Pacific salmon and speculative links to salmon farming in British Columbia

Donald J. Noakes^{*}, Richard J. Beamish, Michael L. Kent

Science Branch, Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, BC, Canada V9R 5K6

Abstract

Pacific salmon abundance along the West Coast of Canada has been in sharp decline since the early 1990s. Declines have been most severe for coho and chinook salmon despite large additions of hatchery-reared fry and smolts. There is particular concern for populations of wild coho because, in addition to low abundance, up to 80% of the juvenile coho in the coastal waters has been identified as being produced by enhancement projects. The most likely reasons for the decline in Pacific salmon stocks include a combination of climate change, overfishing, and freshwater habitat destruction. There have also been suggestions that salmon farming in British Columbia has contributed to the decline of salmon stocks. The hypothesized effects of salmon farming include potential ecological interactions as well as disease concerns. In this paper, we consider the effects of climate change on the abundance of wild salmon stocks as well as potential genetic, ecological, and disease concerns. Shifts in climate in 1977 and 1989 resulted in significant changes in production for a number of marine fish species including Pacific salmon. These climate-related changes, combined with local overfishing and the loss of freshwater habitat, have left some salmon stocks at very low levels. Large-scale salmon enhancement projects have also resulted in significant ecological and genetic interactions with wild salmon, particularly for coho and chinook stocks. These interactions have tended to reduce genetic diversity and result in the replacement of wild salmon by hatchery fish. Hatcheries also represent a potential source of disease pathogens although the magnitude of the problem is difficult to quantify because the disease agents of concern are widespread in both wild and hatchery Pacific salmon as well as a number of non-salmonid hosts. In addition, the same antibiotics used in the salmon farming industry are also used in salmon enhancement projects, making it difficult to identify the source of some pathogens. Although farmed salmon are also a potential source for these disease pathogens, surveys of pathogens in wild and hatchery fish show no patterns that could be attributed to salmon farming. Recent improvements in fish husbandry, including the development and widespread use of vaccines, have also reduced the risk of disease transfer from farmed fish to wild or hatchery

^{*} Corresponding author. Tel.: +1-250-756-7040; fax: +1-250-756-7141; e-mail: noakesd@dfp-mpo.gc.ca

fish. The combined evidence indicates that salmon farming, as currently practiced in British Columbia, poses a low risk to wild salmon stocks particularly when compared to other potential factors. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Climate change; Hatchery and wild salmon interactions; Mixed stock fisheries; Fish pathogens; Salmon farming

1. Introduction

Salmon production in the north Pacific has fluctuated widely this century and there is some evidence to suggest that such fluctuations have occurred naturally for hundreds and perhaps thousands of years (Beamish et al., 1999). The most recent increase in production started in 1977 and coincided with significant shifts in climate and the ecosystem of the north Pacific (Ebbesmeyer et al., 1991; Beamish and Bouillon, 1993). By the mid-1980s, total Pacific salmon catch was at record high levels exceeding 900,000 tons annually. Salmon catches in Canada began to decline sharply around 1990 again, coincidentally with a significant shift in the climate/ocean environment of the north Pacific (Beamish et al., 1999, 2000). The declines in salmon catch were most noticeable for coho (*Oncorhynchus kisutch*) and chinook (*O. tshawytscha*) salmon from California to Canada, but salmon catches were also lower in Alaska in 1997 and 1998. In 1998, the total Canadian salmon catch was at the historic low for this century. These declines have resulted in management agencies in both Canada and the United States adopting restrictive harvest strategies and other conservation measures to protect stocks. The situation has also resulted in significant hardship for coastal communities particularly in British Columbia and Alaska.

The reasons for the sharp decline in salmon production are not clear. However, the most likely causes are believed to be climate change, overfishing, and the loss of productive freshwater habitat. The widespread nature of the decline, as well as similar patterns for other marine fish species (Beamish, 1995; Beamish et al., 1999; Clark et al., 1999; King et al., 1999), strongly suggests that climate change is a key (perhaps dominant) factor influencing salmon production. As such, any action taken to address overfishing and to protect habitat must be viewed within the context of the overall carrying capacity of the ecosystem. It is also important to take into consideration other activities, such as the significant salmon enhancement activities around the Pacific rim, because the introduction of these fish constitutes a major human intervention. Each year, more than 5 billion juvenile salmon from hatcheries, spawning channels, and lake enrichment programs are released into the north Pacific by Canada, United States, Japan and Russia (Mahnken et al., 1998). These fish, henceforth referred to as 'hatchery fish', contribute substantially to fisheries in each country, but the scientific evidence suggests that these large enhancement activities also have significant adverse effects on both wild salmon production as well as the entire ecosystem (Meffe, 1992; NRC, 1996; Grant, 1997; Brannon et al., 1998; Waples, 1999).

The worldwide growth in salmon farming has certainly changed the economic viability of the wild salmon fishery. Farmed salmon have replaced wild salmon in many traditional markets, and the accompanying economic consequences have compounded

the problems resulting from declining catches in the fishery. It has also been suggested that the growth of salmon farming has negatively affected the production of wild Pacific salmon in Canada. The potential effects of escaped farm fish on wild fish include ecological and genetic interactions between escaped farmed salmon and wild or hatchery salmon as well as disease concerns (Anonymous, 1997; Gross, 1998). The British Columbia Environmental Assessment Office undertook a thorough evaluation of salmon farming and considered the key issues of escaped farm fish, fish health, waste management, interactions with other species such as marine mammals, farm siting, as well as various socio-economic factors. The 18-month public review process resulted in a report to the British Columbia government in August 1997. The overall conclusion of the review was “that salmon farming in BC, as currently practiced and at current production levels, presents a low overall risk to the environment” (Anonymous, 1997).

In their review, the Environmental Assessment Office focused on information, scientific or otherwise, that was directly related to salmon farming in British Columbia. Indeed, that was their mandate and report and the associated recommendations were thorough and comprehensive within that context. The review was not intended to, nor did the review specifically address issues related to the decline of Pacific salmon stocks or the fishery. This paper extends the scope of the Environmental Assessment Review to consider various factors that could have contributed to the decline of wild and hatchery salmon stocks in British Columbia. The issues considered include the effects of climate change on salmon production in the north Pacific including stocks in British Columbia, the implications of various enhancement activities, and salmon farming. Our purpose is to provide a broader appreciation of the complex factors influencing our Pacific salmon stocks and fisheries as well as to place in context potential genetic, ecological, and disease concerns. This context is important because decisions on the shared use of our coastal waters involve tradeoffs among the various competing user groups each with their own objectives and views.

2. Climate change

There is a growing body of scientific evidence to support the conclusion that climate change affects marine productivity in general and the production of Pacific salmon specifically (Beamish, 1993, 1995; Francis and Hare, 1994; Hare and Francis, 1995; Ware, 1995; Steele, 1996, 1998; Beamish et al., 1997a,b, 1999; Coronado and Hilborn, 1998; Clark et al., 1999; King et al., 1999). Beamish et al. (1999) considered six indices of climate change in the northern hemisphere and found that shifts between different levels of productivity (regimes) for Pacific salmon were coincidental with shifts in the various climate indices. These regime shifts simultaneously affected North American and Asian-origin Pacific salmon stocks as well as other marine species such as Pacific halibut (*Hippoglossus stenolepis*) (Clark et al., 1999) and sablefish (*Anoplopoma fimbria*) (King et al., 1999). While climate change will undoubtedly affect the freshwater phase of a salmon's life cycle, changes in the marine survival of hatchery salmon as well as in the growth and survival of other marine species suggest that the effect is also very significant during their marine life stage.

To illustrate the effect of climate change on salmon production, we use the all-nation (Canada, United States, Japan and Russia) catch of sockeye, pink and chum salmon as an indicator of salmon productivity in the north Pacific. The catch of these three species represents about 90% of the total salmon catch (Beamish and Bouillon, 1993; Beamish et al., 1999). Also, the management of these fisheries generally involves extensive use of test fisheries and in-season adjustments to fishing plans that have resulted in fairly stable rates of harvest over time. Thus, catch provides a reasonable index of overall salmon production that includes both catch and the number of salmon returning to rivers, lakes, and hatcheries to spawn. Catches have fluctuated substantially since the 1920s, and there are clear periods of above- and below-average productivity (Fig. 1). Following a period of relatively low productivity extending from the mid-1940s, salmon catch increased substantially beginning in 1977. Salmon catches reached record high levels by the mid-1980s and began declining sharply in some areas in the 1990s. The decreases were particularly dramatic for North American stocks at the southern limit of their distribution including Canada (Fig. 2).

We use the integrated Aleutian Low Pressure Index (ALPI) (Beamish et al., 1999) to represent climate change in the north Pacific (Figs. 1 and 2). The Aleutian low is the major weather system during the winter months in the north Pacific and affects our coastal climate as well as upwelling in the north Pacific Ocean. Upwelling occurs when nutrient-rich water is brought from depth to the surface. The increase in nutrients stimulates primary productivity and eventually influences fish production as energy is

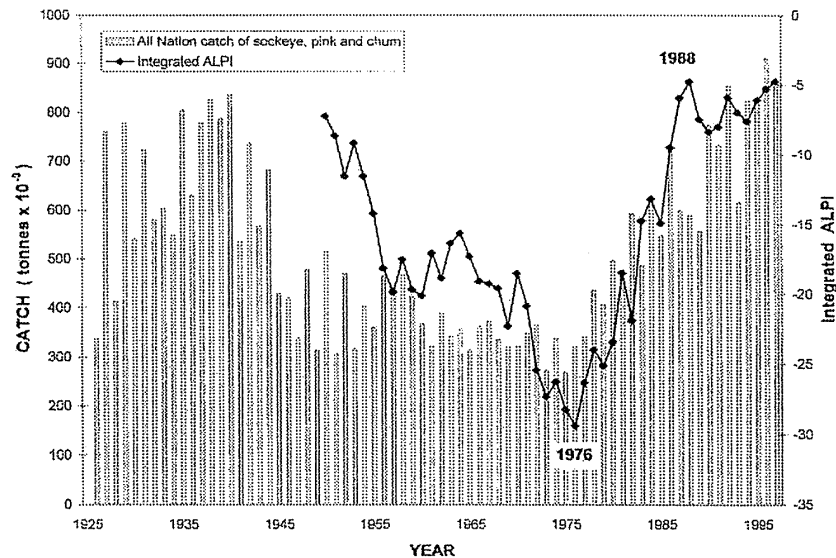


Fig. 1. All-nation (Canada, United States, Japan, and Russia) catches (bars) of sockeye, pink, and chum salmon for the period 1925–1997. Integrated ALPI, 1950–1997.

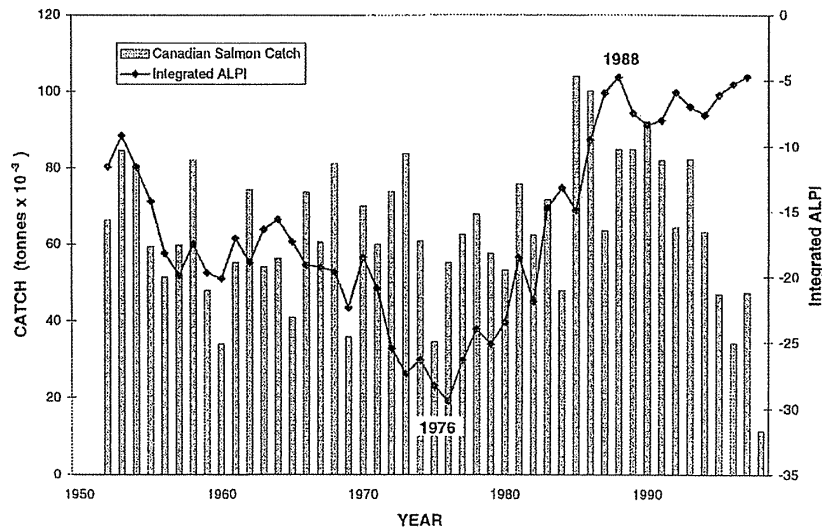


Fig. 2. Canadian salmon (sockeye, pink, chum, chinook, and coho) catches (bars) for the period 1952–1997. Integrated ALPI, 1950–1997.

transferred up through the food chain. The ALPI is defined as the average area in which the pressure is 100.5 kPa or less from December through March (Beamish and Bouillon, 1993). This period coincides with the shift to general winter climate conditions in the north Pacific as well as overlapping with a critical period in the marine life stage for Pacific salmon. The integrated ALPI is developed by taking the cumulative sum of the annual ALPI anomalies calculated by subtracting the overall mean from the annual ALPI (Beamish et al., 1999). The resulting index provides an enhanced visualization of trends in the series. A positive slope in the integrated ALPI indicates above-average intensity of the ALPI and a decreasing slope indicates below-average intensities (Figs. 1 and 2).

Because pressure data before 1950 are less reliable, we have only shown the integrated ALPI since that time (Beamish et al., 1999). Changes in the integrated ALPI trend indicate shifts in climate with periods of increasing integrated ALPI generally corresponding to favorable conditions for marine productivity. The relationship between the intensity of the ALPI and salmon production is complex and the response of the ecosystem will, in part, depend on the state of the ecosystem when the climate shift occurs. Also, there is no guarantee that a return to 'average' climate conditions in the future will result in a return to 'average' stock conditions for all species, given the complex ecological interactions. Certainly, stock rebuilding or stock rehabilitation programs need to consider this important fact in setting realistic objectives or targets.

A period of intense Aleutian lows began in 1977 and coincided with a significant increase in sockeye, pink, and chum salmon catches in the North Pacific (Figs. 1 and 2).

The timing also coincided with the development of significant salmon enhancement programs by Pacific rim countries, and it is plausible that these activities contributed to the rapid rise in productivity aided by favorable environmental conditions. In contrast, survival rates for Strait of Georgia stocks of chinook and coho declined substantially after the 1977 regime shift despite the continued release of millions of hatchery salmon (Figs. 3 and 4). The trend for chinook and coho is opposite the general response for sockeye, pink, and chum stocks. One explanation for this response may be that these chinook and coho salmon tend to rear in more coastal waters than do sockeye, pink, and chum salmon. Increases in the abundance of other marine species (such as Pacific herring and Pacific hake in the Strait of Georgia) likely resulted from a shift in the coastal ecosystem which made it more difficult for juvenile chinook and coho to compete. These changes may also explain the altered marine distribution of coho salmon, especially for stocks that were normally resident in the Strait of Georgia and now migrate to waters off the West Coast of Vancouver Island (Beamish et al., 2000).

The climate shifted to a new regime in 1989/1990 but not back to the pre-1977 state (Beamish et al., 1999). This regime shift once again coincided with significant reductions in Canadian salmon stocks, and the effect on Canadian chinook and coho stocks has been particularly dramatic (Beamish et al., 1995, 1997a,b). The lower survival rates for coho resulted in the closure of directed coho fisheries in British Columbia during the

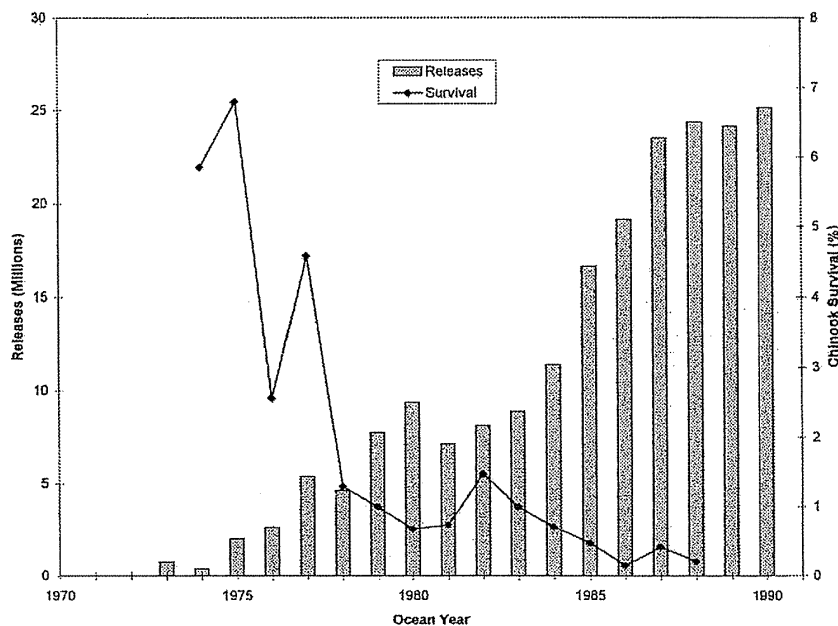


Fig. 3. Estimated hatchery releases and survival rates for Strait of Georgia hatchery chinook salmon.

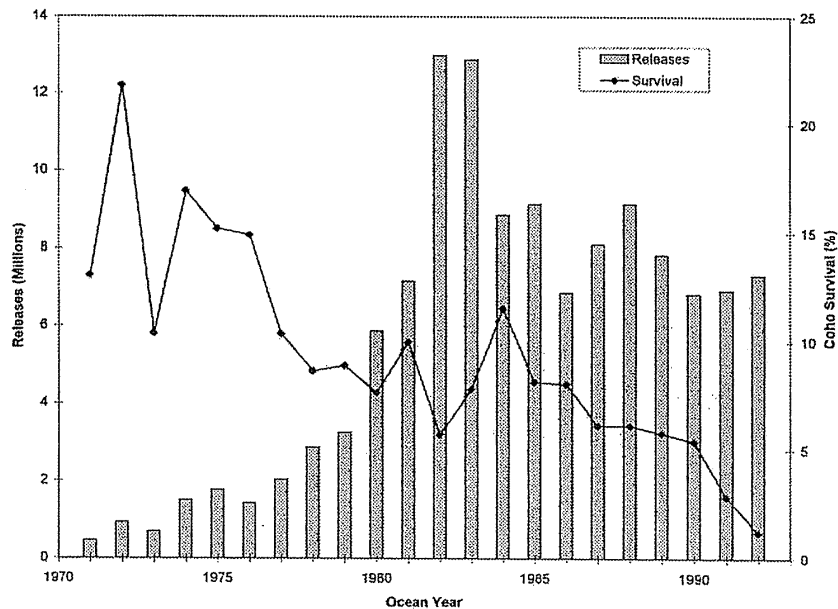


Fig. 4. Estimated hatchery releases and survival rates for Strait of Georgia hatchery coho salmon.

1998 season with similar restrictions likely in 1999 and for the next few years. Consecutive poor returns for the past few years and the persistence of unfavorable environmental conditions may keep stocks at low levels for some time. While these climate shifts have a significant (and perhaps dominant) effect on the overall abundance of salmon, it is also clear that overfishing can result in severe local declines in abundance. Harvesting strategies and other conservation measures need to be designed with these major shifts in the ecosystem in mind. There is also a clear need to educate the public about these issues to ensure that their expectations are realistic.

3. Salmon enhancement

Salmon enhancement has been practiced intensively in British Columbia since the early 1970s (Anonymous, 1998). In each of the last 20 years, nearly 500 million hatchery or enhanced salmon have been produced and released in British Columbia coastal waters (Table 1). Sockeye salmon enhancement represents roughly 40% of the total and is primarily a result of production from artificial spawning channels or lake enrichment (fertilization) programs. Chum and pink salmon enhancement is from both

Table 1
Releases of juvenile salmon from Salmon Enhancement Program facilities in British Columbia

Brood year	Chinook	Chum	Coho	Pink	Sockeye ^a	Total
1977	13,620,370	54,031,652	5,058,281	31,029,220	201,309,000	305,048,523
1978	14,253,404	54,524,319	4,857,722	1,268,250	141,574,350	216,478,045
1979	16,379,080	82,652,695	8,756,923	36,254,543	220,701,122	364,744,363
1980	19,850,845	106,217,696	7,719,900	38,852,965	199,054,901	371,696,307
1981	17,428,192	129,893,114	12,277,121	92,109,022	211,604,372	463,311,821
1982	24,854,529	166,389,988	17,760,471	10,928,339	218,317,433	438,250,760
1983	29,374,066	178,391,768	22,625,999	106,863,812	144,301,195	481,556,840
1984	34,864,768	167,775,075	25,259,448	16,512,153	254,991,214	499,402,658
1985	42,761,623	158,534,388	19,141,208	80,406,993	175,808,962	476,653,174
1986	53,840,001	198,818,282	22,594,254	55,936,910	200,924,044	532,113,491
1987	63,693,726	199,054,154	17,819,451	61,138,919	158,654,299	500,360,549
1988	64,528,141	228,053,816	22,030,433	106,523,161	231,737,734	652,873,285
1989	63,628,249	203,541,458	23,276,342	70,654,343	223,568,392	584,668,784
1990	66,461,805	218,150,978	22,413,456	77,412,349	258,861,158	643,299,746
1991	59,540,198	200,152,670	22,147,770	62,785,065	277,228,098	621,853,801
1992	58,038,721	228,417,050	18,718,352	45,940,900	276,430,119	627,545,142
1993	51,094,315	216,634,268	19,220,749	65,091,522	192,659,518	544,700,372
1994	54,176,102	215,923,666	23,264,803	67,425,282	160,575,488	521,365,341
1995	45,370,507	155,671,013	20,343,257	60,366,993	120,842,893	402,594,663
1996	57,483,942	140,238,676	17,087,290	14,779,572	252,059,228	481,648,708
Average	42,562,129	165,153,336	17,618,662	55,114,016	206,060,176	486,508,319

^aIncludes lake enrichment projects.

hatcheries and spawning channels and represents about 35% and 10% of the total, respectively. Chinook and coho salmon are of particular significance to the sport fishery and, on average, 42.5 million chinook and 17.6 million coho fry and smolts are released from hatcheries and other enhancement projects annually (Table 1).

In addition to British Columbia salmon enhancement activities, the United States also releases significant numbers of hatchery salmon each year (Beamish et al., 1997a; Didier, 1998; Mahnken et al., 1998). Alaskan salmon enhancement began in the mid-1970s and is primarily focused on the production of sockeye, pink, and chum salmon with recent combined annual releases for these three species in the neighborhood of 1.25 billion fish (Beamish et al., 1997a; Mahnken et al., 1998). Salmon enhancement in Washington state began in 1895 and by the early 1950s, more than 100 million chinook and coho salmon were being produced and released each year (Beamish et al., 1997a). In contrast to the situation in British Columbia and Alaska, the bulk of the Washington, Oregon, Idaho, and California enhancement efforts are focused on the production of chinook and coho salmon. In the 1990s, approximately 250 million hatchery chinook and 68 million hatchery coho, or roughly five times the Canadian production for these two species combined, were released annually by Washington, Oregon, Idaho, and California (Table 2). The ecological and economic consequences of these enhancement activities are believed to be considerable because the distributions of many of the salmon stocks and species overlap in the ocean and the returning salmon are jointly harvested in a gauntlet of mixed-stock fisheries in both Canadian and United

Table 2
Estimated enhanced salmon releases from Washington, Oregon, California, and Idaho, 1993–1997

Year	Chinook	Coho	Chum	Pink	Sockeye	Total
1993	210,387,445	68,586,446	59,773,153	0	3,492,161	342,239,205
1994	258,621,084	72,053,589	59,997,531	3,482,400	8,628,644	402,783,248
1995	287,691,217	71,591,160	59,141,900	100,000	16,397,960	434,922,237
1996	259,185,757	72,288,540	58,651,021	4,591,440	5,792,978	400,509,736
1997	232,847,517	55,067,267	42,048,963	0	14,470,295	344,434,042
Average	249,746,604	67,917,400	55,922,514	1,634,768	9,756,408	384,977,694

States waters. Also, these data do not include releases from community salmon enhancements projects operated by non-profit societies and other groups. The number of community enhancement projects has grown substantially in the past few years and their production, particularly for coho and chinook salmon, will increase the total number of hatchery (enhanced) salmon released and reported in Tables 1 and 2.

When salmon enhancement programs were being initiated, there was a common belief that the productive capacity of the Pacific Ocean was vastly underutilized with respect to wild salmon production. In part, this belief stemmed from the relatively large catches of wild salmon in the early part of this century compared to the much smaller catches during the 1950s and 1960s (Fig. 1). Salmon enhancement was seen as a means to compensate for declining freshwater production (lost through urbanization or the construction of control structures/dams on rivers) or to take advantage of unproductive (or barren) freshwater systems. In Canada, the original goal of the Salmon Enhancement Program in the mid-1970s was to double salmon production.

By the mid-1980s, concerns and questions were being raised about the dramatic drop in survival for hatchery coho and chinook salmon in British Columbia (Figs. 3 and 4). Similar concerns had been raised in the United States (Washington State) in the early-1970s about its hatchery programs and, in retrospect, this was an ominous foreshadowing of the problems in British Columbia. To address this issue, several studies were initiated to determine the optimal size and time of release of hatchery salmon to maximize survival (Bilton et al., 1982). Despite these efforts, overall survival for hatchery chinook and coho salmon continued to decline, particularly marine survival.

A comparison of survival for hatchery and wild salmon is difficult primarily because of the lack of good data for wild stocks. It is generally accepted that survival in the early freshwater stages is substantially better for hatchery reared salmon. There is also some evidence (see, e.g., Solazzi et al., 1990) to suggest that hatchery fry outplanted in streams have better survival rates than wild fry due to a size advantage for the hatchery fish. Solazzi et al. (1990) also noted that the hatchery coho generally returned to spawn earlier than the wild coho, but the resultant offspring from the adult hatchery coho had poorer survival. Wild coho generally returned to spawn later in the season although some wild coho also spawned early. It is quite likely that differences in spawning time are designed to buffer the effects of environmental variation and that the percentage of early and late spawning wild coho shifts over time to adapt. Solazzi et al. (1990) also found that for the 30 streams in Oregon considered in their study, the number of adult

coho caught in fisheries or returning to spawn was not substantially influenced by the level of enhancement as measured by the number of fry outplanted.

The information for British Columbia is much more limited, with only three wild indicator streams actively monitored for Strait of Georgia coho stocks and no experiments on the same or similar scale to Solazzi et al. (1990). Marine survival rates are calculated using coded wire tags (approximately 1-mm long notched wire tags inserted into the nose cartilage of the juvenile salmon) recovered from ocean fisheries. Various subjective expansion factors are used to multiply the number of tags recovered to estimate production and survival rates. Although reasonably good estimates of the number of juvenile coho (and other salmonids) released from hatcheries are available, the same is not necessarily true for the wild indicator stocks. In some years, a high percentage (more than 60%) of the adults returning to the wild indicator streams does not have coded wire tags (Simpson et al., 1999) and is not included in the marine survival rate calculation. These untagged fish are either stray hatchery fish from nearby hatcheries or represent the returns from wild juveniles that were missed during the extensive monitoring and tagging programs conducted each year. Also, tagging for the wild coho indicator streams generally takes place during a fixed period each year and juvenile coho migrating downstream either before or after this fixed tagging window are missed. The exclusion of the unmarked adult fish, as well as potential problems stemming from not tagging an unknown portion of the juvenile coho, may result in a significantly biased estimate of the marine survival for the wild fish. Thus, on the basis of the available information, it is not possible to quantify any differences in marine survival rates for wild and hatchery coho in British Columbia. There is also considerable cause for concern over the potential ecological and genetic consequences of very high straying rates (60% or more of the returning adults in some years) of hatchery fish into wild coho streams. The Pacific Fisheries Resource Conservation Council noted in their 1998–1999 annual report that many of these small hatchery or enhancement projects may have done irreparable genetic damage to small stocks of wild chinook and coho salmon (Anonymous, 1999).

It is possible, however, to examine the relative abundance of hatchery and wild coho. Surveys of juvenile salmon in the Strait of Georgia and British Columbia coastal waters indicated that between 70% and 80% of the juvenile coho salmon is now of hatchery origin (Beamish et al., 1998; Zhang and Beamish, 1999). Also, some hatchery managers have suggested that up to 50% of the salmon spawning in rivers with hatcheries is first-generation hatchery fish. These are in addition to the hatchery fish that may stray into streams without hatcheries to spawn with wild salmon (Simpson et al., 1999). Depending on your point of view, these fish and their offspring could be viewed as 'wild' fish although there are serious genetic issues to consider (Hindar et al., 1991). It is clear that hatchery salmon have replaced wild salmon and efforts are required to protect wild stocks.

Enhancement activities have changed over the past century, but it is clear that some practices have negatively affected wild stocks (Meffe, 1992; NRC, 1996; Brannon et al., 1998; Waples, 1999). For instance, it was common practice at many hatcheries to combine sperm from many male salmon during fertilization to minimize the negative consequences of one or more males being infertile. However, analysis of this practice

indicated that significant genetic diversity could be lost in the process because fertilization of the eggs was likely highly uneven among males (Gharrett and Shirley, 1985; Withler, 1988; Withler and Beacham, 1994). It was also common practice to move eggs or fry among hatcheries either to address shortfalls in egg take targets or to simply disperse genetically distinct stocks widely. For example, fish from the Robertson Creek Hatchery were transplanted to the barren Thornton Creek (both on the West Coast of Vancouver Island). Genetic analysis confirmed that the Robertson Creek transfers were responsible for the chinook salmon run now established in Thornton Creek (Withler et al., 1994). Extensive transplantation of sockeye salmon within the Fraser River watershed has also resulted in significant gene flow in that system (Foerster, 1946). Following the rockslide in the Fraser Canyon in 1913 that devastated some salmon runs in the upper Fraser River, transplant efforts that had begun before 1900 were intensified. Hundreds of millions of sockeye salmon eggs and fry were transferred to lakes and streams in an effort to rebuild runs (Ricker, 1987; Roos, 1991). While most of the transfers were unsuccessful, there is evidence that at least some of the transfers were successful (Foerster, 1968; Williams, 1987; Withler et al., 2000). The transfers were also not restricted to fish from within the Fraser system nor were they always from lower Fraser River stocks to upper Fraser River stocks. In 1932, kokanee eggs from Kootenay Lake (in the Columbia River system) were transferred to Cultus Lake (in the lower Fraser River system) and in 1950, eggs from the Thompson River (upper Fraser) were transferred to Portage Creek (mid-Fraser). Also, in years of low sockeye salmon abundance in the Stuart system (upper Fraser River), eggs were transplanted to the Stuart system from Babine Lake and the Skeena River system in northern British Columbia (Ricker, 1987). Molecular genetic information from each of the stocks receiving transplants indicates that the transfers were, at least in part, successful (Withler et al., 2000) although as noted earlier, most of the attempted transfers were unsuccessful or at least their success was undetectable given the current technology.

Another common practice is the release of fed coho fry from hatcheries into rivers and streams (outplanting) within a particular watershed. The larger hatchery fry have been found to replace smaller wild fry and a number of studies (Nickelson et al., 1986; Solazzi et al., 1990; Reisenbichler, 1996) have shown that this practice can reduce the productivity of these populations. In some cases, the releases have been significant with more than 10,000 fish/km of stream outplanted in years when the streams were likely to be already fully seeded by progeny from wild spawners (Pitre and Cross, 1992). It is likely that both short- and long-term ecological and genetic consequences resulted from these activities, although no quantitative studies have been conducted.

Another plausible factor likely contributing to the differential abundance of wild and hatchery salmon is selectivity in mixed stock fisheries. In mixed stock fisheries, the catch is composed of salmon from a variety of wild and hatchery stocks and the various stocks are frequently subjected to differential harvest rates. This is particularly true when fewer wild salmon are mixed with a large number of co-migrating hatchery salmon. In such cases, the wild stocks could be driven close to extinction if fishing activity is biased toward the wild fish. The problem is compounded when stocks are in decline because fishing plans are established on pre-season estimates of returns with some in-season adjustment. The actual harvest rate (calculated only after the fishing season

ends) can be much higher than the pre-season target harvest rate if salmon abundance is declining, thus increasing the probability of smaller runs of salmon being fished to near extinction levels. If stocks are in a natural decline due to unfavorable environmental conditions (such as the 1989/1990 regime shift), overall abundance of both hatchery and wild stocks can be driven down quickly if fishing pressure is maintained at too high a level. The effect will be most dramatic for wild stocks that are at low abundance relative to hatchery stocks. In such cases, one would expect a shift to a higher proportion of hatchery juvenile fish in surveys and also more hatchery fish in the catch. The data certainly suggest that a replacement of wild fish with hatchery fish is possible, with a resultant loss of wild stocks (Beamish et al., 1997a).

4. Salmon farming

Salmon aquaculture began in British Columbia in the late 1970s and after modest growth, the industry went through a major rationalization exercise in the late 1980s. Growth in the British Columbia industry has been limited in the 1990s (Table 3) with the gradual move from Pacific salmon to the more domesticated Atlantic salmon in the early 1990s. The farming of Atlantic salmon had been allowed in Washington state for a number of years before Atlantics were allowed to be raised in British Columbia. Expansion in the industry has been constrained in the last 3 years by a moratorium imposed by the British Columbia provincial government. Current farmed salmon

Table 3
British Columbia farmed salmon production (dressed tons), 1981–1998
NA, not applicable.

Year	Atlantic	Chinook	Coho	Total
1981	NA	NA	149	149
1982	NA	36	195	231
1983	NA	47	62	108
1984	NA	36	543	580
1985	NA	46	577	623
1986	NA	74	258	331
1987	NA	804	669	1474
1988	68	3017	2352	5436
1989	1085	7215	1538	9838
1990	1517	10,150	1279	12,946
1991	3344	17,488	486	21,318
1992	6215	10,636	655	17,506
1993	11,308	9010	2417	22,735
1994	12,824	6706	859	20,389
1995	16,011	7131	680	23,822
1996	16,900	7530	720	25,150
1997	26,336	5203	975	32,514
1998	30,165	7114	1976	39,255

production in British Columbia is approximately 39,000 tons (dressed weight). To put this level of production in perspective, the world production of farmed salmon is roughly 800,000 tons (dressed weight) annually and the fishery for Pacific salmon is about 850–900,000 tons (round weight) (Beamish et al., 1999). Catches in the commercial salmon fishery in British Columbia for all species of salmon are at the low end of the historical record and were approximately 29,000 tons (round weight) in 1998 (Wallace et al., 1998).

The debate on whether to allow Atlantic salmon to be farmed in British Columbia was and continues to be heated. Faced with the reality that Atlantic salmon were being raised in the adjacent waters of Puget Sound, the decision to allow the culture of Atlantic salmon in British Columbia was made in mid-1980s. Strict controls were put in place to minimize the risk of disease transfer. In particular, the Atlantic Salmon Importation Policy specifies that only surface disinfected eggs from certified hatcheries can be imported into British Columbia. In reality, very few eggs are imported into British Columbia although there will likely be additional requests for importation to accommodate future industry expansion. The eggs-only importation policy was deemed to be as restrictive as possible to protect the health of wild, hatchery, and farmed salmon while still adhering to issues associated with international trade. The measures in place have also proved to be effective in controlling disease transfers (Carey and Pritchard, 1995).

In addition to disease concerns, potential ecological interactions between escaped Atlantic and wild/hatchery Pacific salmon have also been raised and debated (Anonymous, 1997; Gross, 1998). These include the establishment of feral populations, hybridization with Pacific salmon, and competition during spawning and juvenile phases. In part, these concerns stem from experiences in Europe and eastern North America where escaped farmed Atlantic salmon have interacted with wild and hatchery Atlantic salmon (Wu, 1995; Fleming and Einum, 1997; Jonsson, 1997; McVicar, 1997). These issues are, however, more relevant to interactions between escaped farmed Pacific salmon and, to a much larger degree, interactions between hatchery and wild salmon. After reviewing the available scientific literature and listening to arguments presented by interested parties, the British Columbia Environmental Assessment Review concluded "... the risk of escaped Atlantic salmon causing lasting harm appears to be so low that there is no demonstrable basis at this time for discontinuing their culture in BC." (Anonymous, 1997). While this conclusion is somewhat reassuring, it is important that efforts to reduce the number of escaped farmed salmon continue in order to minimize the potential ecological and genetic concerns as well as the economic loss to farmers. This is particularly important given the expected continued growth of the industry.

Farmed salmon escape from netpens due to human error and natural causes (such as nets being ripped by marine mammals) and are recovered in both saltwater fisheries and in coastal rivers and streams (Thomson and McKinnell, 1993, 1994, 1995, 1996, 1997; Thomson and Candy, 1998). Reported escapes of Atlantic salmon in British Columbia average 30,000 fish/year (Table 4) although leakage or unreported escapes may double this value. Marine recoveries are a function of both the age and number of escaped fish as well as the fishing effort in the area and time of the escape. For instance, more than 4500 Atlantic salmon were recovered in 1993, a year in which escapes were relatively

Table 4

Reported escapes, as well as marine and freshwater recoveries, of Atlantic salmon in British Columbia, 1991–1997

1998 numbers include reports to October 1998.

Year	Escapes	Marine recoveries	Freshwater recoveries
1991	6651	31	8
1992	9544	349	48
1993	10,000	4543	23
1994	63,809	1037	50
1995	51,883	648	57
1996	11,167	671	235
1997	17,936	2655	155
1998	74,521	130	60
Average	30,689	1258	80

modest (Table 4). In this case, a large escape of large fish coincided in time and location with a seine fishery in Johnstone Strait, where many of the escaped Atlantic salmon were caught. In addition to the escapes in British Columbia, there have also been significant escapes (369,000 fish in one case) of Atlantic salmon in Puget Sound and these fish are also intercepted in British Columbia waters. There are also escapes of Pacific salmon from aquaculture operations but these are generally quite small in recent years, given the move by industry to raise Atlantic salmon (Table 3).

Recoveries of Atlantic salmon in freshwater have been variable and are also a function of the effort involved in monitoring returns of Pacific salmon to coastal streams. A major initiative to monitor Pacific salmon stocks on the West Coast of Vancouver Island was started in 1996, and the increased number of freshwater recoveries of Atlantic salmon in 1996 and 1997 could, in part, be a function of this increased effort as well as recent large escapes in Washington state (McKinnell and Thomson, 1997). The Environmental Assessment Review (Anonymous, 1997) concluded that natural spawning of Atlantic salmon was improbable but not impossible. Recent evidence suggests that two pairs of Atlantic salmon spawned in the Tsitika River on Vancouver Island produced 12 offsprings. These juvenile Atlantic salmon were removed from the Tsitika and there is no evidence to suggest that a sustaining population will be established. The removal of the juvenile fish and past experience would suggest that this outcome is highly unlikely. Given the unfavorable marine survival conditions for Pacific salmon including steelhead trout (Welch et al., 2000), it is unreasonable to assume that progeny from Atlantic salmon would fare any better than Pacific salmon in the foreseeable future.

With the encouragement and support of various fishing interests, several attempts were made earlier this century to establish natural runs of Atlantic salmon in British Columbia rivers. Despite the best efforts of those involved, none of the attempts was successful. Millions of eggs and fry were planted in streams but there were no documented reports of successful spawning or the return of adults in large numbers. This is not surprising because there are no reports of Atlantic salmon establishing self-sus-

taining anadromous populations outside their home range (McKinnell and Thomson, 1997; McKinnell et al., 1997) although some land-locked stocks have been established.

Hybridization among Pacific salmon species has been studied and researchers have found viable and, in some cases, fertile hybrid progeny (Foerster, 1935). Hybridization between Atlantic and Pacific salmon has not been studied extensively but studies have resulted in extremely poor survival (see, e.g., Blanc and Chevassus, 1979; Loginova and Krasnoperova, 1982; Gray et al., 1993). The most recent laboratory study conducted by Fisheries and Oceans Canada involved all possible reciprocal crosses between Atlantic, coho, chinook, pink, chum, and sockeye salmon as well as cutthroat, steelhead, and domestic rainbow trout (R.H. Devlin, unpublished data). The highest frequency of survival to hatching was observed for Atlantic-pink and Atlantic-steelhead crosses with survivals ranging from 0.4% to 6%. Survivals to hatching for other Atlantic–Pacific hybrids were much lower, in the range of 0–0.12%. The surviving progeny exhibited physical deformities (such as curvature of the spine) and none of the hybrid fish displayed any signs of maturity up to 4 years post-hatch. It is important to note that all trials were conducted under controlled laboratory conditions and none of the Atlantic–Pacific hybrid fish would be expected to survive in the wild. It is also theoretically possible for an Atlantic salmon to attempt to mate with a Pacific salmon in the wild and thereby disrupt the reproduction of the Pacific salmon. There is no evidence of such an event occurring, and the likelihood of such an event is low given the few number of Atlantic salmon observed in freshwater systems. The Environmental Assessment Review (Anonymous, 1997) concluded that the likelihood and resultant risk of hybridization between Atlantic and Pacific salmon are extremely low.

The potential interaction between escaped farmed Pacific salmon and wild or hatchery Pacific salmon raises genetic and ecological concerns similar to those associated with hatchery-reared fish, especially transplanted hatchery stocks. The move away from farming Pacific salmon to farming Atlantic salmon, and the reduced number of escaped farmed Pacific salmon in recent years have reduced but not eliminated these risk. However, the risks to wild Pacific salmon are far greater from the large salmon enhancement programs both due to the significant number of hatchery fish released and the transfer of hatchery fish throughout the Pacific Northwest over the last century (Meffe, 1992; NRC, 1996; Grant, 1997; Brannon et al., 1998).

5. Fish health

Disease transfer has and continues to be one of the key concerns raised by environmentalists with respect to salmon aquaculture. The concerns relate to the introduction of exotic pathogens to British Columbia, the amplification of pathogens in farmed fish, as well as the use of antibiotics to control diseases. As noted previously, an eggs-only importation policy has been adopted in British Columbia and this policy has proven effective in minimizing the risk associated with introducing an exotic disease (Carey and Pritchard, 1995). To date, all of the pathogens found in farmed fish are endemic to the Pacific region and have existed in British Columbia for some time (Kent and Poppe, 1998; Kent et al., 1998).

The public perception is that 'wild' implies 'pristine' and that wild fish are thus disease-free. Of course, this is not true and in the case of Pacific salmon, parasites have frequently been used as natural tags to distinguish different stocks (Margolis, 1963, 1998; Beacham et al., 1998). In fact, the use of parasites as natural tags played a key role in the management of the early high seas fisheries for salmon as well as providing valuable information on the ocean distribution of salmon stocks from around the Pacific rim (Margolis, 1963). In a recent survey of Pacific salmon and non-salmonid species, Kent et al. (1998) found that pathogens of concern to wild, hatchery, and farmed salmon were widespread both geographically and by species. For example, the prevalence of *Renibacterium salmoninarum*, the cause of bacterial kidney disease (BKD), is about the same in ocean-caught Pacific salmon as in healthy farmed salmon. Furthermore, *Loma salmonae*, a serious microsporidian pathogen of pen-reared chinook salmon was found in all species of ocean-caught Pacific salmon in British Columbia (Kent et al., 1998), and this pathogen has recently been a problem in sockeye salmon in the Babine system in northern British Columbia (where netpen farming does not occur). Wild fish (both Pacific salmon and non-salmonid species) act as reservoirs for a wide variety of pathogens, and new hosts are being found on a regular basis. The widespread and common occurrence of these endemic pathogens make it difficult to infer causal links (transfers), but it is reasonable to assume that such transfers occur.

Our best long-term record of fish disease prevalence in British Columbia is for salmon enhancement facilities because they, like fish farms, provide a convenient venue for study. A survey of our fish health records (D. Kieser, personal communication) showed relatively consistent patterns of disease outbreaks reported from 1975 through 1997 (Table 5). The search was restricted to pathogens deemed to be of particular concern (D. Kieser, personal communication) and included Infectious Hematopoietic Necrosis virus (IHNV), *Yersinia ruckeri* (the cause of enteric redmouth disease), *Aeromonas salmonicida* (the cause of furunculosis), *Renibacterium salmoninarum* (the cause of BKD), and *Ceratomyxa shasta*. The report summarizes cases where there were significant fish losses (i.e., above a pre-set threshold mortality rate such as a few percent mortality per month) or where specific health checks were conducted, possibly prompted by previous disease outbreaks at the hatchery in question or in the screening of potential broodstock for hatchery production. In some cases, up to 80% of the potential broodstock has been screened due to disease concerns in areas where salmon farming is not practiced (D. Kieser, personal communication). The search does not include less serious disease outbreaks or disease problems involving community enhancement projects which primarily involved the culture of coho and chinook salmon. Disease problems at hatcheries operated by the Province of British Columbia were not included in this survey. In general, there are very few records of disease outbreaks associated with community enhancement projects both from a lack of awareness of the problem and a lack of expertise to identify the pathogens of concern and their associated disease symptoms. However, it is reasonable to assume that disease problems in community projects are, at least, equal to the levels detected in hatcheries, and possibly higher if eggs and wild fry from different watersheds are mixed together in the same rearing tanks or ponds. This practice, common at some but not all community enhancement projects, can facilitate the transfer of disease among stocks.

Table 5

Number of cases investigated at salmon enhancement facilities due to losses at the hatchery or health checks involving BKD, furunculosis, IHNV, *Y. ruckeri* (enteric redmouth) and *C. shasta*

Year	Coho	Chinook	Chum	Sockeye	Pink	Steelhead	Total
1975	11	7				1	19
1976	22	4			1	1	28
1977	16	3		2			21
1978	21	1	1	3	1		27
1979	13	2			1		16
1980	22	1	1			5	29
1981	31	2			1	6	40
1982	19	6	2			12	39
1983	9	5		1		7	22
1984	23	4		1		10	38
1985	17	1	1			3	22
1986	13	5		2		3	23
1987	10	10		1		2	23
1988	15	8	1	2	1	4	31
1989	19	1		1	2	2	25
1990	25	8				3	36
1991	27	6				5	38
1992	29	12	2			5	48
1993	26	3	2	2		9	42
1994	10	12		1		1	24
1995	22	11				2	35
1996	6	5		1		2	14
1997	10	1		1		2	14
Total	416	118	10	18	7	85	654
Cases/year	18.1	5.1	1.4	1.5	1.2	4.3	28.4

In general, the longer fish are kept in captivity at the hatchery, the greater the potential for the detection and reporting of serious disease outbreaks (Table 5). Coho salmon experienced the most serious disease outbreaks (averaging 18 disease outbreaks per year) because most hatcheries release the coho as smolts 1 year after hatching or 18 months after fertilization. Chinook salmon at five disease cases per year were second, and this is again consistent with the tendency for these fish to remain at the hatchery for longer periods of time than other species of salmon excluding coho. Chinook salmon are often released at an earlier age from hatcheries (usually before 1 year) than coho, and this helps explain the lower incidence of disease outbreaks despite the higher levels of production. In some cases, the fish were treated with antibiotics (when appropriate) and released. Fish were destroyed only in extreme cases, such as a serious IHNV outbreak in chum salmon at the Kitimat hatchery.

Antibiotic (or antimicrobial) drug use is of concern for two reasons. First, there is concern that antibiotics will act to select for antibiotic-resistant strains of bacteria that will negatively affect treatment of these pathogens at publicly funded hatcheries, public or private enhancement projects, and private aquaculture operations. Second, there is concern that residual antibiotics will be absorbed by other marine species (particularly invertebrates) and either be consumed directly by humans or continue to select for

antibiotic-resistant strains of bacteria and transfer this resistance to other bacteria. These issues are not new and are of particular concern in the agri-food industry where significant quantities of antibiotics are employed both for promotion of growth and therapeutic purposes (Khachatourians, 1998).

An average of 156 g of antibiotics was used to produce a ton of farmed Atlantic salmon in British Columbia in 1995 (P. Hewitt, BC Min. Agric. Fish. Food, personal communication). More than 80% of the antibiotics was used for fish weighing less than 2 kg or for broodstock. A high percentage (roughly 90%) of the antibiotics used was oxytetracycline, which, as studies have shown, is quickly associated with either magnesium or calcium molecules in seawater and rendered biologically unavailable (Barnes et al., 1990; Lunestad and Goksoyr, 1990; Pursell et al., 1996; Smith et al., 1996). The introduction and widespread use of vaccines to control vibriosis and furunculosis in the aquaculture industry have significantly decreased the amount of antibiotics used in recent years. Similar trends have been seen in other major salmon-producing countries such as Norway, where roughly 6 g of antibiotics was required for each ton of production in 1996 vs. 900 g per ton of production in 1987 (Markestad and Grave, 1996). One of the differences in the British Columbia industry is that the production of chinook salmon constitutes roughly 30% of the total British Columbia production (Table 3). BKD is a significant problem for chinook salmon, and antibiotics are sometimes used to treat outbreaks of the disease. A vaccine for BKD is currently being tested and if the results are positive, the widespread use of this vaccine will decrease antibiotic usage in the British Columbia industry further.

In addition to the development and use of vaccines, there have been changes in fish husbandry practices that have improved the general overall health of farmed salmon. Research aimed at matching the nutritional requirements of the fish at various stages in their life cycle and the nutritional composition of fish feed has resulted in healthier fish and considerable reductions in FCRs to approximately 1.15–1.20 for Atlantic salmon and 1.7–2.0 for Pacific salmon (Anonymous, 1997). These improvements have reduced the amount of solid waste at farm sites resulting from uneaten food and have improved the efficient use of antibiotics. There is also the assumption that farmed salmon are more stressed than wild salmon since they are caged and live at higher densities. There is certainly no evidence to support the assertion that farmed fish are more stressed than the ‘fight or flee’ world of wild salmon. St. Hilaire et al. (1999) compared stressors affecting wild and farmed fish, and concluded that wild fishes are not necessarily subjected to fewer stressors.

A complicating factor is the use of a wide range of antibiotics, antimicrobials, pesticides, and other materials at salmon and trout enhancement facilities. Oxytetracycline, erythromycin, romet 30, sulfamerazine, furazolidone, chloramphenicol, oxolinic acid, diquat, malachite green, chloramine T, and a number of other agents have been used at Canadian hatcheries and community enhancement projects since the early 1970s. Some of these have undoubtedly resulted in the selection of antibiotic/antimicrobial-resistant bacteria, making it difficult to identify the potential source of the disease problem. This situation also highlights the type of the resource use conflicts that need to be considered in making public policy decisions. For instance, some groups involved in salmon enhancement activities are encouraging limiting the use of antibiotics in the

aquaculture industry with the expectation that the use of the same antibiotics will improve the treatment of disease problems at enhancement facilities.

6. Summary

It is clear that a complex set of factors led to the decline of wild and hatchery Pacific salmon stocks in Canada. A regime shift in 1977 resulted in a period of high productivity in the North Pacific Ocean and an increase in the abundance of sockeye, pink, and chum stocks. Another regime shift in 1989/1990 resulted in a change in the ecosystem to one that was less favorable to salmon production and, in general, a decline in salmon production of all species particularly at the southern limits of their freshwater distribution. Overfishing during this decline likely also contributed to the problem. In addition to these natural shifts in climate, global warming induced by human activity may be occurring and this will also impact biological systems in the future. There is, however, insufficient information to separate the two climate effects (Corti et al., 1999; Hasselmann, 1999). In addition to a general warming of our oceans, most scientists expect to see, as a result of global warming, more intense climatic extremes that will trigger or result in major changes in the ecosystem. The intense El Niño in 1997 and the La Niña in 1998 are examples of such extremes.

The extensive salmon enhancement programs in Canada and the United States have done much to raise public awareness of the importance to protect salmon habitat. Public education and participation are absolutely essential if wild salmon stocks are to be protected for future generations. However, recent reviews of large-scale hatchery programs (Meffe, 1992; NRC, 1996; Grant, 1997; Brannon et al., 1998; Waples, 1999) have raised concerns about their overall benefit particularly given the potentially serious genetic, ecological, and disease problems that have been identified. In the past, the success of hatchery programs was judged on the number of juvenile salmon produced and released as well as the net increase in salmon catch. There is now a growing recognition that these enhancement initiatives need to be judged and managed according to their overall impact on our ecosystem. It is clear that a more holistic ecosystem approach is required to understand these complex interactions.

The potential ecological and genetic effects of escaped farm fish (both Atlantic and Pacific salmon) also need to be considered in a broader context. While Atlantic salmon is an exotic species, evidence presented at the British Columbia Environmental Assessment Review suggests a low overall risk to Pacific salmon (Anonymous, 1997). This is not to say concerns over escaped Atlantic salmon should be dismissed. Rather, improvements in containment, codes of practice, and performance standards should be adopted to further reduce potential risks. These measures are particularly important given the likelihood of industry expansion. Escaped farm Pacific salmon pose a greater potential risk given their ability to breed and interact with wild and hatchery salmon. The limited data available preclude an in-depth assessment although it is likely that potential interactions would be localized to areas near the point of the escape. The scale of salmon enhancement activities in both Canada and the United States would suggest a far greater risk to wild stocks from salmon enhancement operations.

Potential disease problems have also been raised with respect to salmon farming. While disease can be a problem on salmon farms, the widespread use of vaccines and improved husbandry practices have generally improved the health of farmed salmon as indicated by the substantial reduction in antibiotic use in the industry. Also, surveys of wild salmonid and non-salmonid fish and shellfish show that pathogens of concern are both common and widespread geographically including areas where salmon farming is not practiced (Kent et al., 1998). The issue of antibiotic use in salmon aquaculture is of particular concern. A complicating factor is the widespread use of the same antibiotics in salmon enhancement projects, making it very difficult to precisely identify the source of the disease agent and to demonstrate cause and effect of fish disease relationships. When viewed in this broader context, the evidence to date, with respect to the prevalence of pathogens as well as the frequency and pattern of disease outbreaks both now and in the past, indicates that salmon aquaculture is not having a significant incremental impact on wild and hatchery Pacific salmon. It is clear, however, that a more comprehensive review of disease issues including ongoing monitoring of wild, enhanced, and farmed salmon is required to resolve the concerns raised.

With respect to declines in Pacific salmon, the evidence suggests that salmon aquaculture in British Columbia has not had a significant impact especially when viewed in the context of the other factors that have likely contributed to the decline. There are, however, potential risks that need to be addressed and improvements are possible that would further reduce the risk of potential environmental problems (Anonymous, 1997). Action should be taken to move forward with these initiatives.

Acknowledgements

Partial support for the climate research was provided by the Professional Partnerships Program administered by the Canadian Association of Universities and College. Ruth Withler and three anonymous reviewers also provided useful comments and suggestions. Coilin Wallare assisted in the preparation of this manuscript.

References

- Anonymous, 1997. Salmon aquaculture review: report of the Environmental Assessment Office, Summary plus Vols. 1–5. BC Environmental Assessment Office, 1203 pp. plus appendices.
- Anonymous, 1998. An assessment of Canadian hatchery salmon production 1977–1997. North Pacific Anadromous Fish Commission, Doc. No. 322. Department of Fisheries and Oceans, Canada, 18 pp.
- Anonymous, 1999. Pacific Fisheries Resource Conservation Council 1998–1999 Annual Report. Vancouver, BC, 237 pp.
- Barnes, A.C., Lewin, C.S., Hastings, T.S., Amyes, S.G.B., 1990. Cross-resistance between oxytetracycline and oxolinic acid in *Aeromonas salmonicida* associated with other membrane changes. Microbiol. Lett. 72, 337–340.
- Beacham, T.D., Margolis, L., Nelson, R.J., 1998. A comparison of methods of stock identification for sockeye salmon (*Oncorhynchus nerka*) in Barkley Sound, British Columbia. North Pacific Anadromous Fish Commission Bull. No. 1, 227–239.
- Beamish, R.J., 1993. Climate and exceptional fish production off the West Coast of North America. Can. J. Fish. Aquat. Sci. 50, 2270–2291.

- Beamish, R.J. (Ed.), 1995. Climate change and northern fish populations. Can. Spec. Publ. Fish. Aquat. Sci., Vol. 121, 739 pp.
- Beamish, R.J., Bouillon, D.R., 1993. Pacific salmon production trends in relation to climate. Can. J. Fish. Aquat. Sci. 50, 1002–1016.
- Beamish, R.J., Riddell, B.E., Neville, C.-E.M., Thomson, B.L., Zhang, Z., 1995. Declines in chinook salmon catches in the Strait of Georgia in relation to shifts in the marine environment. Fish. Oceanogr. 4, 243–256.
- Beamish, R.J., Mahnken, C., Neville, C.M., 1997a. Hatchery and wild production of Pacific salmon in relation to large-scale, natural shifts in the productivity of the marine environment. ICES J. Mar. Sci. 54, 1200–1225.
- Beamish, R.J., Neville, C., Cass, A.J., 1997b. Production of Fraser River sockeye salmon (*Oncorhynchus nerka*) in relation to decadal-scale changes in the climate and the ocean. Can. J. Fish. Aquat. Sci. 54, 543–554.
- Beamish, R.J., Sweeting, R., Zhang, Z., 1998. Estimating the percentage of hatchery-reared coho salmon in the Strait of Georgia in 1997. Pacific Stock Assessment Review Committee Working Paper S98-8.
- Beamish, R.J., Noakes, D.J., McFarlane, G.A., Klyashtorin, L., Ivanov, V.V., Kurashov, V., 1999. The regime concept and natural trends in the production of Pacific salmon. Can. J. Fish. Aquat. Sci. 56, 516–526.
- Beamish, R.J., Noakes, D.J., McFarlane, G.A., Pinnex, W., Sweeting, R., King, J., 2000. Trends in coho marine survival in relation to the regime concept, in review.
- Bilton, H.T., Alderdice, D.F., Schnute, J.T., 1982. Influence of time and size at release of juvenile coho salmon (*Oncorhynchus kisutch*) on returns at maturity. Can. J. Fish. Aquat. Sci. 39, 426–447.
- Blanc, J.M., Chevassus, B., 1979. Interspecific hybridization of salmonid fish: I. Hatching and survival up to the 15th day after hatching F1 generation hybrids. Aquaculture 18, 21–34.
- Brannon, E., Lichatowich, J., Currens, K., Riddell, B., Goodman, D., Williams, B., Mc Connaha, C., 1998. Review of salmonid artificial production in the Columbia River basin. Northwest Power Planning Council, Doc. No. 98-33.
- Carey, T.G., Pritchard, G.I., 1995. Fish health protection: a strategic role in Canadian fisheries management. North Am. J. Fish. Manage. 15, 1–13.
- Clark, W.G., Hare, S.R., Parma, A.M., Sullivan, P.J., Trumble, R.J., 1999. Decadal changes in growth and recruitment of Pacific halibut (*Hippoglossus stenolepis*). Can. J. Fish. Aquat. Sci. 56, 242–252.
- Coronado, C., Hilborn, R., 1998. Spatial and temporal factors affecting survival in coho salmon (*Oncorhynchus kisutch*) in the Pacific northwest. Can. J. Fish. Aquat. Sci. 55, 2067–2077.
- Corti, S., Molteni, F., Palmer, T.N., 1999. Signature of recent climate change in frequencies of natural atmospheric circulation regimes. Nature 398, 799–802.
- Didier, A.J., Jr., 1998. Estimates of salmon harvests and hatchery releases in Washington, Oregon, California, and Idaho, 1993–1997. North Pacific Anadromous Fish Commission, Doc. No. 359. Pacific States Marine Fisheries Commission, OR, 14 pp.
- Ebbesmeyer, C.C., Cayan, D.R., McLain, D.R., Nichols, F.H., Peterson, D.H., Redmond, K.T., 1991. 1976 step in the Pacific climate: forty environmental changes between 1968–1975 and 1977–1984. In: Betancourt, J.L., Tharp, V.L. (Eds.), Proc. Seventh Annual Pacific Climate (PACCLIM) Workshop, April 1990. Edited by California Dep. Water Resour. Interagency Ecol. Stud. Program Tech. Rep. No. 26, pp. 115–126.
- Fleming, I.A., Einum, S., 1997. Experimental tests of genetic divergence of farmed from wild Atlantic salmon due to domestication. ICES J. Mar. Sci. 54, 1051–1063.
- Foerster, R.E., 1935. Interspecific cross-breeding of Pacific salmon. Trans. R. Soc. Can., Series 3, Vol. 29, Section 5, pp. 21–33.
- Foerster, R.E., 1946. Restocking depleted sockeye salmon areas by transfer of eggs. J. Fish. Res. Board Can. 6, 483–490.
- Foerster, R.E., 1968. The sockeye salmon; *Oncorhynchus nerka*. Fish. Res. Board Can. Bull. 162, 422.
- Francis, R.C., Hare, S.R., 1994. Decadal-scale regime shifts in the large marine ecosystems of the Northeast Pacific: a case for historical science. Fish. Oceanogr. 3, 379–391.
- Gharrett, A.J., Shirley, S.M., 1985. A genetic examination of spawning methodology in a salmon hatchery. Aquaculture 47, 245–256.

- Grant, W.S., 1997 (Ed.). Genetic effects of straying of non-native hatchery fish into natural populations: proceedings of the workshop. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS-NWFSC-30, 130 pp.
- Gray, A.K., Evans, M.A., Thorgaard, G.H., 1993. Viability and development of diploid and triploid salmonid hybrids. *Aquaculture* 112, 125–142.
- Gross, M.R., 1998. One species with two biologies: Atlantic salmon (*Salmo salar*) in the wild and in aquaculture. *Can. J. Fish. Aquat. Sci.* 55 (Suppl. 1), 131–144.
- Hare, S.R., Francis, R.C., 1995. Climate change and salmon production in the northeast Pacific Ocean. In: Beamish, R.J. (Ed.), *Climate Change and Northern Fish populations*. *Can. Spec. Publ. Fish. Aquat. Sci.*, Vol. 121, pp. 357–372.
- Hasselmann, K., 1999. Linear and nonlinear signatures. *Nature* 398, 755–756.
- Hindar, K., Ryman, N., Utter, F., 1991. Genetic effects of cultured fish on natural fish populations. *Can. J. Fish. Aquat. Sci.* 48, 945–957.
- Jonsson, B., 1997. A review of ecological and behavioral interactions between cultured and wild Atlantic salmon. *ICES J. Mar. Sci.* 54, 1031–1039.
- Kent, M.L., Poppe, T.T., 1998. Diseases of seawater netpen-reared salmonid fishes. *Fisheries and Oceans — Canada. Pacific Biological Station, Nanaimo, BC, Canada*, 138 pp.
- Kent, M.L., Traxler, G.S., Kieser, D., Richard, J., Dawe, S.C., Shaw, R.W., Prosperi-Porta, G., Ketcheson, J., Evelyn, T.P.T., 1998. Survey of salmonid pathogens in ocean-caught fishes in British Columbia, Canada. *J. Aquat. Anim. Health* 10, 211–219.
- Khachatourians, G.G., 1998. Agricultural use of antibiotics and the evolution and transfer of antibiotic-resistant bacteria. *Can. Med. Assoc. J.* 159, 1129–1136.
- King, J., McFarlane, G.A., Beamish, R.J., 1999. Decadal scale patterns in the relative year-class success of sablefish (*Anoplopoma fimbria*). *Fisheries Oceanography* (in press).
- Loginova, G.A., Krasnoperova, S.V., 1982. An attempt at crossbreeding Atlantic salmon and pink salmon (preliminary report). *Aquaculture* 27, 329–337.
- Lunestad, B.T., Goksoyr, J., 1990. Reduction in the antibacterial effect of oxytetracycline in sea water by complex formation of magnesium and calcium. *Dis. Aquat. Org.* 9, 67–72.
- Mahnken, C., Ruggerone, G., Waknitz, W., Flagg, T., 1998. A historical perspective on salmon production from Pacific rim hatcheries. *North Pacific Anadromous Fish Commission Bull. No. 1*, 38–53.
- Margolis, L., 1963. Parasites as indicators of the geographic origin of sockeye salmon. *Oncorhynchus nerka* (Walbaum), occurring in the North Pacific Ocean and adjacent seas. *Int. North Pacific Fish Commission Bull.* 11, 101–156.
- Margolis, L., 1998. Are naturally occurring parasite 'tags' stable? An appraisal from four case histories involving Pacific salmonids. *North Pacific Anadromous Fish Commission Bull. No. 1*, 205–212.
- Markestad, A., Grave, K., 1996. Reduction in antibacterial drug use in Norwegian fish farming due to vaccination. *Programme and Book of Abstracts, International Fish Vaccinology, Oslo, June 5–7, 1996*, p. 46.
- McKinnell, S., Thomson, A.J., 1997. Recent events concerning Atlantic salmon escapes in the Pacific. *ICES J. Mar. Sci.* 54, 1221–1225.
- McKinnell, S., Thomson, A.J., Black, E.A., Wing, B.L., Guthrie, C.M. III, Koerner, J.F., Helle, J.H., 1997. Atlantic salmon in the North Pacific. *Aquaculture Research* 28, 145–157.
- McVicar, A.H., 1997. Disease and parasite implications of coexistence of wild and cultured Atlantic salmon populations. *ICES J. Mar. Sci.* 54, 1093–1103.
- Meffe, G.K., 1992. Techno-arrogance and halfway technologies: salmon hatcheries on the Pacific Coast of North America. *Conservation Biology* 6, 350–354.
- Nickelson, T.E., Solazzi, M.F., Johnson, S.J., 1986. Use of hatchery coho salmon pre-smolts to rebuild wild populations in Oregon coastal streams. *Can. J. Fish. Aquat. Sci.* 43, 2443–2449.
- NRC, 1996. *Upstream: Salmon and Society in the Pacific Northwest*. National Research Council Committee on Protection and Management of Pacific Northwest Anadromous Salmonids. National Academy Press, Washington, DC, 452 pp.
- Pitre, K.R., Cross, C., 1992. Impacts of coho enhancement on three Thompson River tributaries. In: Berg, L., Delaney, P.W. (Eds.), *Proceedings of the Coho Workshop, Nanaimo, BC, May 26–28, 1992*, pp. 140–150.
- Pursell, L., Samuelson, O.B., Smith, P., 1996. Reduction in the in vitro activity of flumequine against

- Aeromonas salmonicida* in the presence of the concentration of Mg^{++} and Ca^{++} ions found in seawater. *Aquaculture* 135, 245–255.
- Reisenbichler, R.R., 1996. Genetic factors contributing to declines of anadromous salmonids in the Pacific Northwest. In: Stouder, D.J., Bisson, P.A., Naiman, R.J. (Eds.), *Pacific Salmon and Their Ecosystems, Status and Future Options*. Chapman & Hall, London, pp. 223–244.
- Ricker, W.E., 1987. Effects of the fishery and of obstacles to migration on the abundance of Fraser River sockeye salmon (*Oncorhynchus nerka*). *Can. Tech. Rep. Fish. Aquat. Sci.* 1522, 75 pp.
- Roos, J.F., 1991. Restoring Fraser River salmon. Pacific Salmon Commission, 438 pp.
- Simpson, K., Semple, R., Baillie, S., Adkins, B., Lehmann, S., 1999. Status of coho salmon stocks adjacent to the Strait of Georgia including the lower Fraser River. Pacific Scientific Advice Review Committee Working Paper S99-199, 76 pp.
- Smith, P., Niland, N., O'Domhnaill, F., O'Tuathaigh, G., Hiney, M., 1996. Influence of marine sediment and divalent cations on the activity of oxytetracycline against *Listonella anguillarum*. *Bull. Eur. Assoc. Fish. Pathol.* 16, 54–57.
- Solazzi, M.F., Nickelson, T.E., Johnson, S.L., 1990. An evaluation of the use of coho salmon presmolts to supplement wild production in Oregon coastal streams. Fishery Research Report No. 10. Oregon Dept. Fish and Wildlife, Portland, OR, 26 pp.
- Steele, J.H., 1996. Regime shifts in fisheries management. *Fish. Res.* 25, 19–23.
- Steele, J.H., 1998. Regime shifts in marine ecosystems. *Ecological Applications* 8, 533–536.
- St. Hilaire, S., Kent, M.L., Iwama, G., 1999. Factors affecting the health of farmed and wild fish populations — a perspective from British Columbia, in press.
- Thomson, A.J., Candy, J.R., 1998. Summary of reported Atlantic salmon (*Salmo salar*) catches and sightings in British Columbia and adjacent waters in 1997. *Can. MS Rep. Fish. Aquat. Sci.* 2467, 39 pp.
- Thomson, A.J., McKinnell, S., 1993. Summary of reported Atlantic salmon (*Salmo salar*) catches and sightings in British Columbia in 1992. *Can. MS Rep. Fish. Aquat. Sci.* 2215, 15 pp.
- Thomson, A.J., McKinnell, S., 1994. Summary of reported Atlantic salmon (*Salmo salar*) catches and sightings in British Columbia and adjacent waters in 1993. *Can. MS Rep. Fish. Aquat. Sci.* 2246, 35 pp.
- Thomson, A.J., McKinnell, S., 1995. Summary of reported Atlantic salmon (*Salmo salar*) catches and sightings in British Columbia and adjacent waters in 1994. *Can. MS Rep. Fish. Aquat. Sci.* 2304, 30 pp.
- Thomson, A.J., McKinnell, S., 1996. Summary of reported Atlantic salmon (*Salmo salar*) catches and sightings in British Columbia and adjacent waters in 1995. *Can. MS Rep. Fish. Aquat. Sci.* 2357, 29 pp.
- Thomson, A.J., McKinnell, S., 1997. Summary of reported Atlantic salmon (*Salmo salar*) catches and sightings in British Columbia and adjacent waters in 1996. *Can. MS Rep. Fish. Aquat. Sci.* 2407, 29 pp.
- Wallace, C.G., Noakes, D.J., Welch, D.W., 1998. An update on trends in catch of Pacific salmon in Canada. North Pacific Anadromous Fish Commission Doc. 317, Dept. of Fisheries and Oceans, Canada, 8 pp.
- Waples, R.S., 1999. Dispelling some myths about hatcheries. *Fisheries* 24, 12–21.
- Ware, D.M., 1995. A century and a half of change in the climate of the NE Pacific. *Fish. Oceanogr.* 4, 267–277.
- Welch, D.W., Ward, B.R., Smith, B.D., Eveson, J.P., 2000. Influence of the 1990 ocean climate shift on British Columbia steelhead (*Oncorhynchus mykiss*). *Fish. Oceanogr.* (in press).
- Williams, I.V., 1987. Attempts to re-establish sockeye salmon (*Oncorhynchus nerka*) populations in the upper Adams River, British Columbia, 1949–84. In: Smith, H.D., Margolis, L., Wood, C.C. (Eds.), *Sockeye Salmon (*Oncorhynchus nerka*) Population Biology and Future Management*. Can. Spec. Publ. Fish. Aquat. Sci. 96, pp. 235–242.
- Withler, R.E., 1988. Genetic consequences of fertilizing chinook salmon (*Oncorhynchus tshawytscha*) eggs with pooled milt. *Aquaculture* 68, 15–25.
- Withler, R.E., Beacham, T.D., 1994. Genetic consequences of the simultaneous or sequential addition of semen from multiple males during hatchery spawning of chinook salmon (*Oncorhynchus tshawytscha*). *Aquaculture* 126, 11–23.
- Withler, R.E., Beacham, T.D., Watkins, R.F., Stevens, T.A., 1994. Identification of farm-reared and native chinook salmon (*Oncorhynchus tshawytscha*) on the west coast of Vancouver Island, British Columbia, using the nuclear DNA probe B2-2. *Can. J. Fish. Aquat. Sci.* 51 (Suppl. 1), 267–276.
- Withler, R.E., Le, K.D., Nelson, J., Miller, K.M., Beacham, T.D., 2000. High levels of intra- and interpopula-

- tion genetic variation in exploited populations of Fraser River sockeye salmon, *Oncorhynchus nerka*, in review.
- Wu, R.S.S., 1995. The environmental impact of marine fish culture: towards sustainable future. *Mar. Poll. Bull.* 31, 159–166.
- Zhang, Z., Beamish, R.J., 1999. Use of otolith microstructure to study life history of juvenile chinook salmon in the Strait of Georgia in 1995 and 1996, in press.