American Fisheries Society Symposium 15:152–160, 1995

Salmon Stock Restoration and Enhancement: Strategies and Experiences in British Columbia

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Abstract.—The use of hatcheries as a resource management tool for chinook salmon *Oncorhynchus tshawytscha* and coho salmon *O. kisutch* in western Canada and United States is being questioned. In British Columbia other salmon species catches have increased substantially since the 1970s, but chinook salmon catch has decreased and many wild coho salmon stocks are declining in abundance. The future role of hatcheries in areas where there remains potential natural salmon production, will likely depend on whether they benefit wild stocks. Such benefits will depend on careful planning and implementation of hatchery projects and operations, avoidance of interactions between hatchery and wild stocks, acquisition of and response to new knowledge, and conservation-driven harvest management. This paper presents three examples of strategies being used and considered in British Columbia to meet these challenges.

Wild coho salmon stocks in the Strait of Georgia are in serious decline. The plan developed to rebuild these stocks is unique in our experience. It integrates harvest at rates sustainable by the wild stocks, freshwater habitat management, and specific stated criteria for hatchery expansion and operations. Stocks will be monitored for two cycles after harvest is reduced. Failure of a large number of stocks to respond will result in further harvest reduction or other measures, not expanded hatchery production. If only a few stocks do not rebuild after two cycles, hatchery augmentation may be considered. Hatchery releases will be limited to levels that will produce an escapement equal to 50% of the natural spawning target. Operational procedures will be in accordance with guidelines intended to minimize ecological and genetic interactions between wild and hatchery coho salmon. Finally, hatchery production will be reduced if there is evidence of negative interactions between wild and hatchery coho salmon in the marine environment.

Coho salmon fry augmentation programs on the Eagle and Coldwater rivers in interior British Columbia are reviewed to examine interactions between wild and hatchery coho salmon during freshwater rearing. The return per spawner for wild spawners and the survival of hatchery fry to catch and escapement decreased at higher spring fry abundance in the Eagle River but not in the Coldwater River. The fry augmentation program has been discontinued in the Eagle River. These results demonstrate that coho salmon fry augmentation may be a beneficial strategy for some stocks but that negative interactions between wild and hatchery coho salmon may occur. The results illustrate the need to monitor and adjust stocking programs. The success of augmentation work designed to rebuild wild stocks ultimately means the hatchery will no longer be required; this suggests portable or temporary hatchery facilities should be considered.

Adult returns from chinook and coho salmon smolts released from Fraser River and coastal hatcheries feeding into the Strait of Georgia are compared with release numbers. There is a relatively strong suggestion of density-dependent mortality for hatchery chinook salmon. Interpretation of the hatchery coho salmon data is more debatable. Progress and problems encountered in designing a large-scale experiment involving manipulation of hatchery-release numbers to test the density dependence hypothesis are described.

Hatchery and spawning channel production of salmon *Oncorhynchus* spp. has been an increasingly important component of fisheries resource management in British Columbia during the past 20 years. In the 1960s and 1970s salmon catches were low compared with the previous 4 decades. This decline provided impetus for the Canadian Salmonid Enhancement Program (SEP), started in 1977. In the 1990s Canadian salmon catch has risen to record levels, partly due to enhancement but primarily due to improved escapement management and favorable ocean conditions (Canadian Department of Fisheries and Oceans [DFO], unpublished data). Most of this recovery has been in sockeye salmon *O. nerka* and pink salmon *O. gorbuscha*, and to less extent chum salmon *O. keta*. The catch of coho salmon *O. kisutch* has been relatively stable during the past 30 years, but many wild stocks are at low levels. Catch of chinook salmon *O. tshawytscha* has declined dramatically.

Perhaps because hatcheries in western Canada and United States are typically associated with chinook and coho salmon, and abundance of many stocks of these species has recently declined, the use of hatcheries is being questioned. The technology is blamed per se, despite the success of hatchery-produced pink and chum salmon in British Columbia, Japan, and Alaska. In the extreme, and more often in the popular media than in scientific reports, hatcheries are blamed for many of the problems facing wild chinook and coho salmon, especially overfishing and failure to protect fish habitat.

It is clear that debate will not resolve this issue. There will undoubtedly continue to be a role for hatcheries as a final resort for conserving threatened stocks and for enhancing discrete fisheries in areas barren of wild stocks. The hatchery's role in areas where there remains significant potential for natural salmon production, however, will likely be dictated by whether or not hatcheries are shown to provide a net benefit for wild stocks. Success will depend on extreme vigilance in the way that hatchery programs are planned and implemented, with emphasis on avoidance of genetic and ecological interactions with wild stocks, acquisition of and response to new knowledge, and conservation-driven harvest management policies. Widespread recognition that hatcheries are a beneficial management tool will be the measure of success.

This report examines some of these requirements for planning and implementation from the perspective of the salmon hatchery program in British Columbia, with emphasis on chinook and coho salmon hatcheries. I describe the most recent example in the evolution of enhancement planning, the goal of which is to assist in the rebuilding of wild stocks. Data that indicate possible negative interactions between wild and hatchery stocks in fresh water and possible intraspecific interactions in the marine environment are presented, and our response to these data is described.

Enhancement Planning

The approach to enhancement planning is very different today than it was 20 years ago, reflecting changing goals. Although much improved, it is not flawless. There remains substantial progress to be made in integration of our enhancement, habitat, and harvest activities. We do not have stock production plans closely linked to harvest plans for most stocks, nor do we have perfect understanding of what is required to maintain genetic diversity when using a hatchery to rebuild wild stocks perfect. Regardless, planning and action are necessary, and we must use the best available information for these purposes.

Wild coho salmon stocks in the Strait of Georgia (Figure 1) were the subject of a recent large-scale planning exercise in British Columbia. Coastal and Fraser River wild stocks that contribute to the Strait of Georgia are declining in abundance. Overfishing and habitat loss were identified as the major causes for the decline. Recommendations from the planning exercise integrate harvest and habitat management, enhancement, and evaluation (DFO 1992). The key action points are to increase spawning escapement through harvest reduction and to increase habitat awareness, protection, and improvement. The SEP's responsibilities include habitat improvement and educational activities, so SEP is an integral part of the key habitat recommendations. What is new in this plan is the emphasis on wild stock harvest management, the highlighting of habitat issues, and stated criteria for hatchery expansion and operations.

New hatchery production is not viewed as part of the initial phase of the plan. Rebuilding will first be attempted using harvest reduction. If, after two cycles, most stocks have responded, hatchery augmentation may be considered for the remainder. Failure of a large number of stocks to show gain after two cycles will result in further harvest reduction or other measures, not expanded hatchery production. The recommended role for hatcheries in rebuilding wild coho salmon in the Strait of Georgia is summarized below.

1. Do not increase hatchery production solely to maintain catch levels during the wild stock rebuilding period.
2. Consider hatcheries to augment stocks that are not rebuilding after two cycles at average exploitation rates in the 65–70% range.
3. Augment stocks in a manner designed to maintain genetic diversity: (a) augmentation should not be necessary for most stocks; (b) native stock should be used; (c) escapement of hatchery-origin adults will not exceed 50% of the total spawning target (50% rule); and (d) hatchery operations will be done in accordance with guidelines intended to minimize negative genetic and ecological interactions.
4. Monitor augmentation efforts including rebuilding effects, genetic composition, and compliance with the 50% rule.
5. Monitor wild and hatchery coho salmon production for evidence of negative interactions in the marine environment; if found, reduce hatchery production.

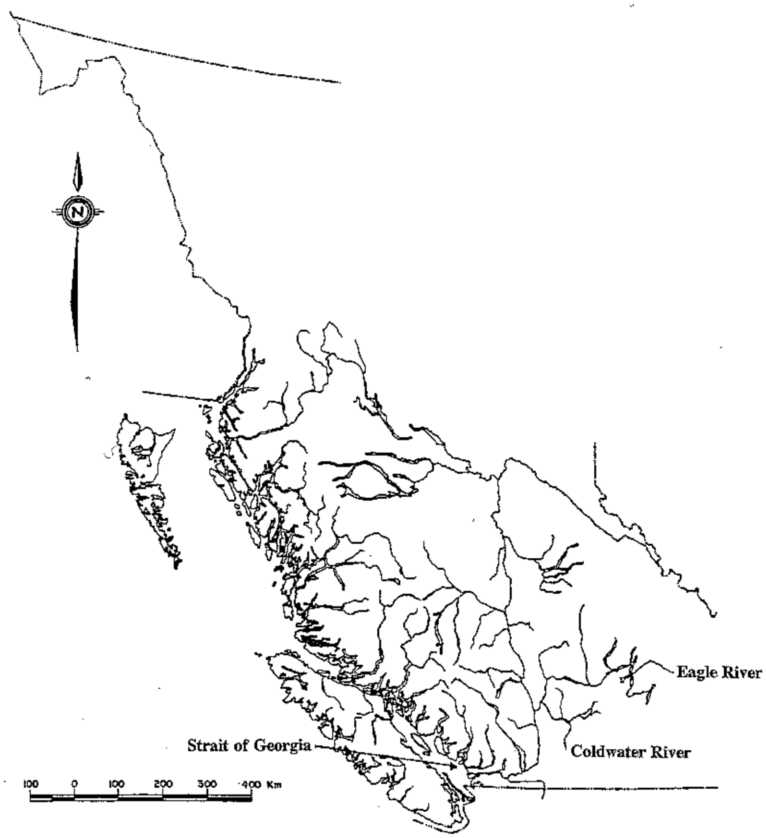

FIGURE 1.—Map of British Columbia showing the location of the Eagle and Coldwater rivers and the Strait of Georgia.

Freshwater Interactions

Hatchery augmentation of coho salmon in the Eagle and Coldwater rivers in interior British Columbia (Figure 1) was designed to use native broodstock and release fry during their first spring. The hatchery production plans were revised in the second year to add smolt releases. The fry generally rear a year in fresh water prior to migrating to sea. These augmentation programs were reviewed by Pitre and Cross (1993), who concluded that hatchery fry releases could increase stock production if habitat was underutilized, but that underestimation of wild fry abundance could lead to negative interactions between wild and hatchery fry.

Eagle River coho salmon escapement showed an initial positive response to hatchery production but has since declined. Escapement in 1991 was the lowest of the study period (Figure 2; Table 1). The ratio of return (catch plus escapement) per spawning adult for wild coho salmon and the survival to return for hatchery fry is plotted against total spring fry number in Figure 3. The hatchery survival data are based on coded wire tag (CWT) studies that involved tagging juveniles and recovering adults in the fisheries and escapement. The wild-origin escapement estimates are calculated from total escapement figures less the number of hatchery fish (from CWT data). The wild-origin catch is then estimated using the exploitation rate data for CWT hatchery coho salmon. Data sources and calculations are described by Pitre and Cross (1993). I estimated the total spring fry population in the river by assuming that each spawning adult produced 200 wild fry (this assumes fecundity is 2,000, egg-to-fry survival is 20%, and females make up 50% of escapement), and summing this estimate with the number of hatchery fry released in the spring (Table 1). The wild return per spawner and the hatchery fry survival data both indicate a decline with increasing fry abundance, suggesting that rearing capacity was exceeded.

Coldwater River data examined in the same way

TABLE 1.—Wild a
equal to catch plus

Brood year	Number of wild spawners	N c (>
1984	6,486	
1985	2,416	
1986	3,766	
1987	9,565	
1988	7,808	
1984	600	
1985	430	
1986	803	
1987	1,061	
1988	1,325	

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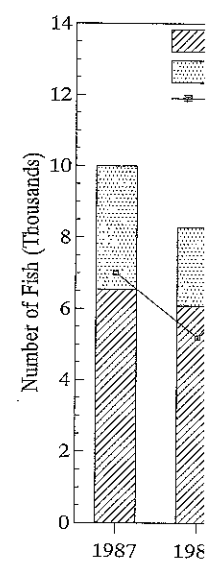

FIGURE 2.—Num
spawning coho salm
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TABLE 1.—Wild and hatchery coho salmon data for the Eagle and Coldwater rivers, British Columbia. Returns are equal to catch plus escapement.

Brood year	Number of wild spawners	Number of wild fry (×1,000)	Number of hatchery fry (×1,000)	Total number of fry (×1,000)	Return year	Returns: Wild origin	Returns: Hatchery origin	Escapement: Wild origin	Escapement: Hatchery origin	Return to spawner ratio for wild spawners	Hatchery fry survival (%)
Eagle River											
1984	6,486	1,297	387	1,684	1987	13,485	7,126	6,540	3,456	2.08	1.29
1985	2,416	483	438	921	1988	19,551	7,046	6,083	2,190	8.09	1.11
1986	3,766	753	327	1,080	1989	7,486	5,132	3,279	2,248	1.99	0.57
1987	9,565	1,913	329	2,242	1990	12,332	3,897	3,315	1,056	1.29	0.63
1988	7,808	1,562	344	1,906	1991	3,871	1,176	1,475	442	0.50	0.24
Coldwater River											
1984	600	120	61	181	1987	4,927	248	1,525	75	8.21	0.34
1985	430	86	111	197	1988	2,539	6,588	549	1,423	5.90	0.91
1986	803	161	332	493	1989	5,453	6,340	1,156	1,344	6.79	0.90
1987	1,061	212	227	439	1990	7,094	5,565	1,681	1,319	6.69	0.84
1988	1,325	265	228	493	1991	5,898	2,822	1,392	666	4.45	0.22

(Figure 4; Table 1) indicate that the hatchery releases have made a significant contribution to the rebuilding of the coho salmon stock. The wild return per spawner ratio and the survival of hatchery fry show no consistent trend relative to estimated fry abundance (Figure 5). The downturn in 1991 returns and survival at both Eagle and Coldwater

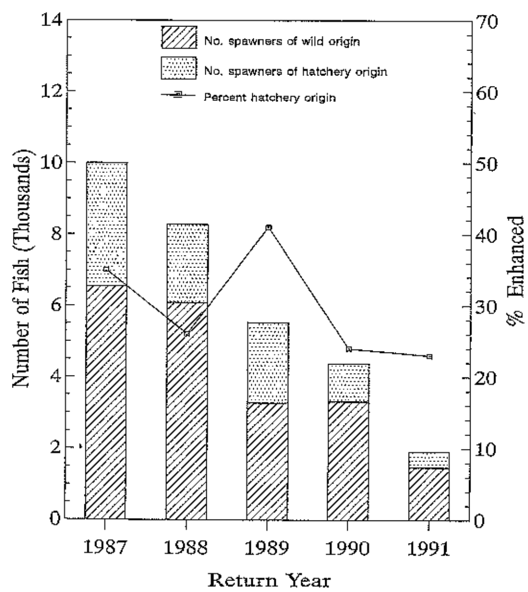

FIGURE 2.—Number of wild- and hatchery-origin spawning coho salmon returning to Eagle River and the percent of return due to hatchery-origin enhancement during 1987–1991 (from Pitre and Cross 1993).

are likely independent of stock-specific activities because returns were generally poor throughout southern British Columbia. The Coldwater hatchery-fry distribution differs from that at Eagle. Eagle hatchery fry are distributed throughout the available coho salmon rearing habitat. Coldwater hatchery fry are released into the upper river, which escaping adults can access only in high-water years. As a result Coldwater fry augmentation appears to be contributing to stock rebuilding with little interaction with the wild coho salmon.

Based on these studies we have discontinued fry releases into the Eagle River. The Coldwater fry program will continue as long as it is making a contribution without reducing wild production. Smolt releases are expected to continue at Eagle River as long as the additional production is needed to reach spawning targets or provide special fishery opportunities. Smolt releases are no longer considered essential for Coldwater coho salmon and have been discontinued.

We learned a number of things from this work that may be generally applicable to other species and stocks. One is that hatchery coho salmon fry may be detrimental to wild fry. Steward and Bjornn (1990) described the potential for competition and predation between wild and hatchery juveniles in streams. Release of hatchery coho salmon fry into naturally seeded areas should reflect carrying capacity estimates and wild fry abundance to avoid direct ecological and potential secondary genetic interactions.

Another lesson is that augmentation can work

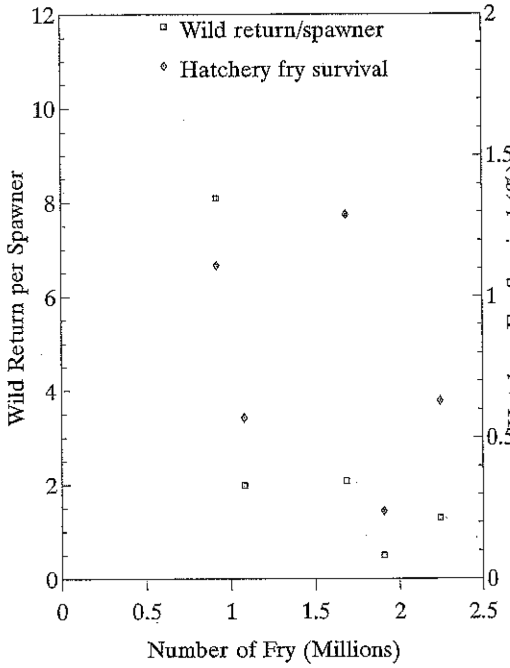

FIGURE 3.—The ratio of wild adult coho salmon return (catch plus escapement) per spawning adult and the survival to return for hatchery fry in relation to total spring fry abundance in the Eagle River during 1984–1988 brood years.

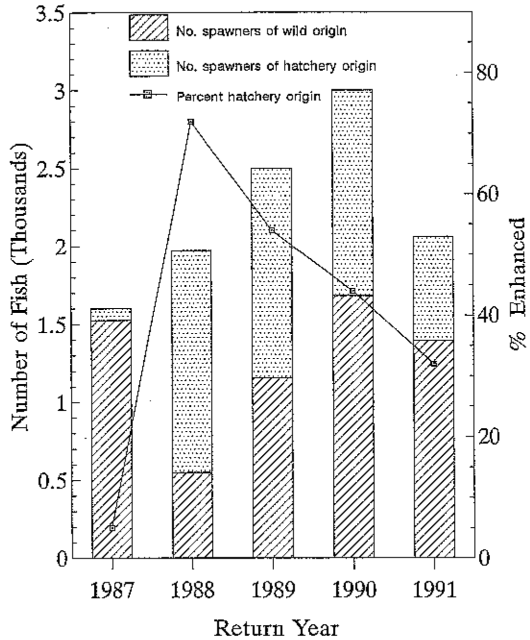

FIGURE 4.—Number of wild- and hatchery-origin spawning coho salmon returning to Coldwater River and the percent of return due to hatchery-origin enhancement during 1987–1991 (from Pitre and Cross 1993).

but populations should be monitored and hatchery release numbers should be adjusted in accordance with wild fry abundance. This is not always a simple process. Assessing natural rearing capacity and wild fry status and identifying any interactions between wild and hatchery salmon is complex and expensive work. We need simple, inexpensive methods that can be applied to a large number of streams each year. In some cases, especially for interior streams, wild adult spawner counts may be a useful index for subsequent wild fry numbers. In other cases a fry indexing system may be feasible. Simple mass-marking techniques for hatchery fish, enabling identification of the origin of returning adults, would be a major advancement.

We also learned the value of better understanding our objectives. Clearly the goal of fry augmentation programs is to rebuild the stock to the point where hatchery fry are all surplus to the natural capacity; that is, to put the hatchery out of business. There are only a few exceptions to this, due to unique habitat conditions. Both the Eagle and Coldwater hatchery coho salmon are produced in permanent facilities. It might be wiser to use portable or temporary hatchery facilities that could be moved to another problem area when the project goals are achieved. Permanent hatcheries situated to enhance several stocks from different streams offer some flexibility but may still outlive their usefulness. Along with permanent hatcheries come staff, local community, and resource user expectations, which complicate reaching a biologically based decision to terminate a hatchery program.

Ocean Interactions

Hatchery production of chinook and coho salmon smolts released from Fraser River and coastal Canadian hatcheries feeding into the Strait of Georgia (Figure 1) have been assessed using CWT marking and recovery since hatchery production of these species was started in 1971. Methodology and data sources are detailed in Cross et al. (1991).

Adult returns for chinook salmon have not increased in direct proportion to the number of smolts released (Figure 6; Table 2). A Beverton–Holt stock recruitment model was fit using log-transformed data (Hilborn and Walters 1992). The average recruitment curve is shown in Figure 6. These data are not adjusted to compensate for

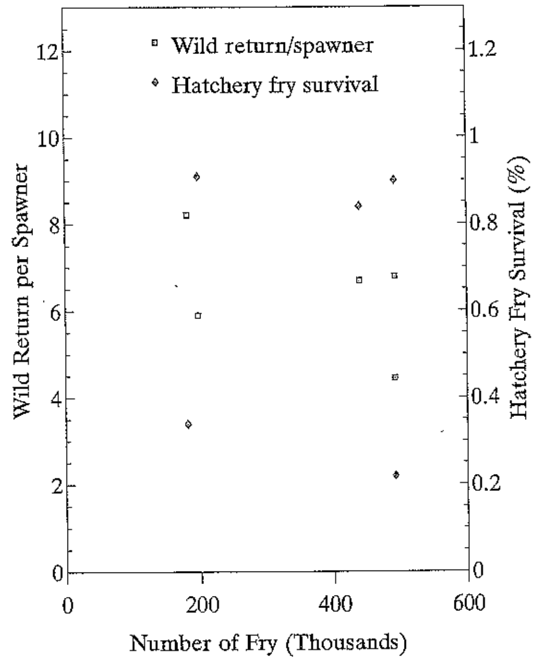

FIGURE 5.—The ratio of wild adult coho salmon return (catch plus escapement) per spawning adult and survival to adult of hatchery fry in relation to total fry abundances in the Coldwater River during 1984–1988 brood years.

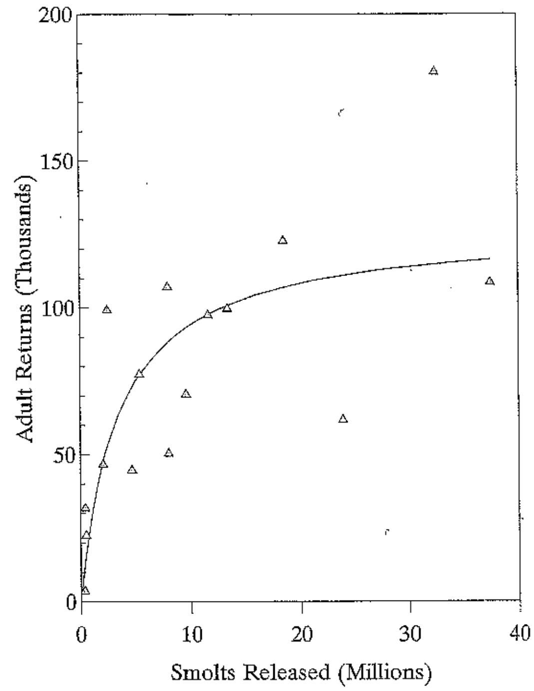

FIGURE 6.—Relationship between the number of returning adult chinook salmon and the number of smolts released from hatcheries in the Strait of Georgia during 1972–1987 brood years.

changes in fisheries regulations that have resulted in increased, unaccounted for, fishing mortality during the study period.

There is a more direct relationship between adult returns and smolt releases for coho salmon than for chinook salmon (Figure 7; Table 2). The Beverton–Holt average recruitment curve is shown for the coho salmon data; linear correlation analysis is also highly significant.

The survival data for Strait of Georgia hatchery chinook salmon suggest possible density-dependent mortality and is reminiscent of Oregon hatchery coho salmon data. The Oregon data have been examined by several authors, recently Emlen et al. (1990). The fundamental issue is whether the apparent decline in return rate (survival) is due to excessive releases of hatchery smolts resulting in density-dependent mortality. With 26 year-classes of wild and hatchery coho salmon data in Oregon the answer is still not clear. Emlen et al. (1990) caution that the conclusion of no density dependence based on earlier analyses (Nickelson 1986) is suspect and that the analyses of Emlen et al. (1990) suggest that density dependence is occurring.

Survival data for Strait of Georgia hatchery coho salmon indicate some reduction at higher smolt numbers but less reduction than that observed for chinook salmon. It is important to note that survival of both chinook and coho salmon declined dramatically in the late 1970s (Table 2). This decline is coincident with an increase in Strait of Georgia surface-water temperature during 1977 that has persisted into the 1990s (Walters 1993).

The concern for Strait of Georgia coho salmon, unlike chinook salmon, is not declining survival of hatchery fish, but the declining abundance of wild coho salmon. The estimated catch of wild Strait of Georgia coho salmon in Canadian fisheries from 1976 to 1989 decreased while the Canadian Strait of Georgia hatchery coho salmon catch increased (DFO 1992; Figure 8). Wild coho salmon escapement also declined (DFO 1992). This has led to speculation that hatchery coho are replacing wild coho salmon.

Walters (1993) described four general hypotheses that may explain the Strait of Georgia wild coho salmon decline: overfishing, freshwater habitat loss, ocean carrying-capacity limitations, and ocean conditions. As noted earlier, DFO has identified over-

TABLE 2.—Hatchery smolt release, adult return, and survival data for Strait of Georgia chinook and coho salmon.

Brood year	Coho salmon: Smolt release	Coho salmon: Adult return	Coho salmon: Survival (%)	Chinook salmon: Smolt release	Chinook salmon: Adult return	Chinook salmon: Survival (%)
1972	448,029	61,958	13.8	883,815	8,026	0.91
1973	771,037	157,399	20.4	811,065	35,596	4.39
1974	2,120,937	228,640	10.8	432,935	32,273	7.45
1975	2,160,224	369,288	17.1	2,090,609	47,271	2.26
1976	2,271,315	351,003	15.5	2,508,259	129,338	5.16
1977	2,597,727	405,551	15.6	5,382,697	78,917	1.47
1978	3,256,738	370,512	11.4	4,681,312	45,550	0.97
1979	3,809,461	353,812	9.3	8,020,445	50,856	0.63
1980	4,142,662	387,079	9.3	9,913,800	72,398	0.73
1981	3,922,413	318,400	8.1	8,141,582	108,354	1.33
1982	5,263,439	568,666	10.8	11,879,505	98,387	0.83
1983	10,789,493	718,588	6.7	14,068,365	107,436	0.76
1984	9,094,886	735,697	8.1	18,187,313	126,777	0.70
1985	6,885,616	830,536	12.1	23,521,329	64,184	0.27
1986	6,933,286	593,481	8.6	30,820,474	182,697	0.59
1987	6,681,796	571,385	8.6	36,981,046	118,531	0.32
1988	7,551,030	505,519	6.7			
1989	7,688,023	477,439	6.2			

fishing and habitat degradation as the most probable causes of the decline. Walters (1993) concludes that density-dependent competition between wild and hatchery coho salmon at sea is the most likely cause but acknowledges that oceanographic change cannot be ruled out. He discounts the overfishing and freshwater habitat hypotheses. Declines in hatchery chinook salmon survival may be due to ocean carrying-capacity limitations or oceano-

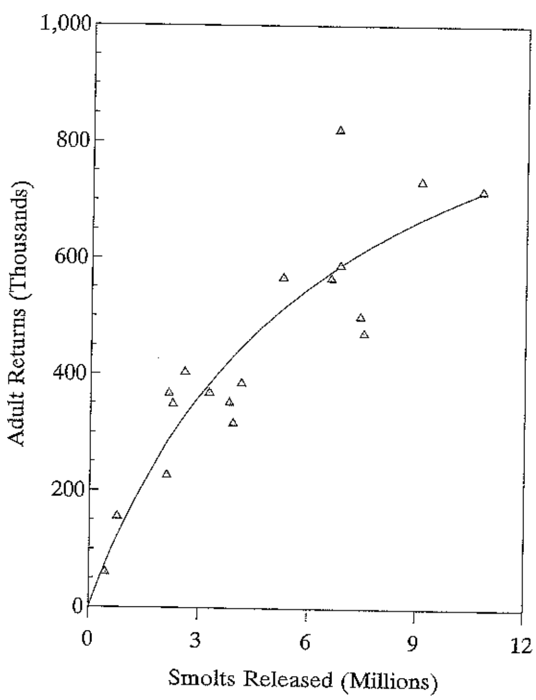

FIGURE 7.—Relationship between the number of returning adult coho salmon and the number of smolts released from Strait of Georgia hatcheries during 1972–1989 brood years.

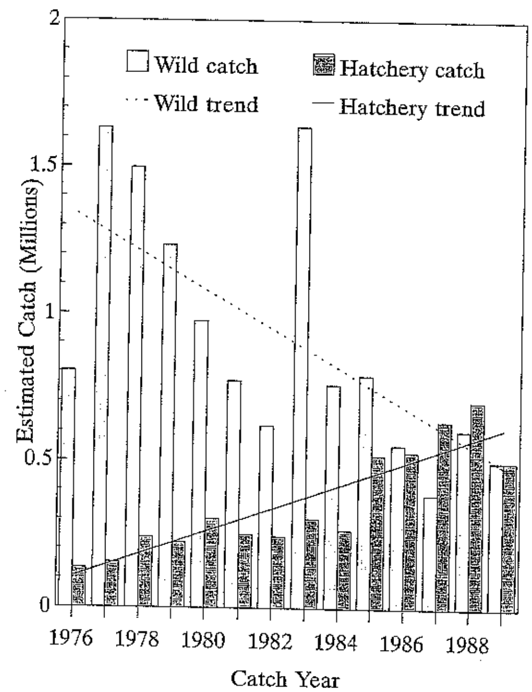

FIGURE 8.—Catch of wild-origin and hatchery-origin Strait of Georgia coho salmon in Canadian fisheries during 1976–1989.

graphic change as described in Walters' coho salmon model; estuarine capacity and smolt quality are other possible causes. Changes in the survival of hatchery chinook salmon are not the result of overfishing or freshwater habitat degradation.

It is not my intent to debate these opposing hypotheses here. Rather I have tried to describe two calamitous biological trends in Strait of Georgia salmon, the decline in survival of hatchery chinook salmon and the decline of wild coho salmon, for which there are no clear explanations. The extended debate in Oregon sends a strong message that continuing the status quo will not produce answers in the near future. Emlen et al. (1990) proposed large-scale experiments, such as described by Walters et al. (1988), to test the density dependence hypothesis for Oregon coho salmon. The DFO scientific and enhancement staff, with input from the University of British Columbia, have already invested considerable effort into design of such an experiment for Strait of Georgia chinook salmon.

A conceptual model for one experimental approach is shown in Figure 9. This experiment would require alternating hatchery production from 50% to 100% of capacity for a number of years. If density-dependent mortality is occurring, survival is expected to increase for small year-classes, resulting in relatively stable adult returns. If there is no density-dependent mortality, survival should vary independent of smolt numbers, and adult returns will be lower on average for small year-classes.

It was our intention to review the finalized design with user groups and, with their concurrence, initiate the experiment as quickly as possible. Two developments have interfered. The first is the increasing concern about density-dependent interactions between wild and hatchery coho salmon among some scientists and their suggestion that it is more important to do the experiment for coho than for chinook salmon. There was consensus that the experiment should be done for only one species at a time. It is important that all parties agree on a detailed design if we hope to agree on the interpretation of results. The second development is the output of experimental design work. While incomplete, preliminary analyses indicate a conclusive experiment for chinook salmon may require 20–30 years. A similar study for coho salmon would likely take 5–10 years. As a result, we must be prepared to make a long-term commitment to the experiment, but the species that most urgently requires study is uncertain. A final decision will depend on our analyses of the probability of success, the risks of the experiment, and the understanding of all interested parties.

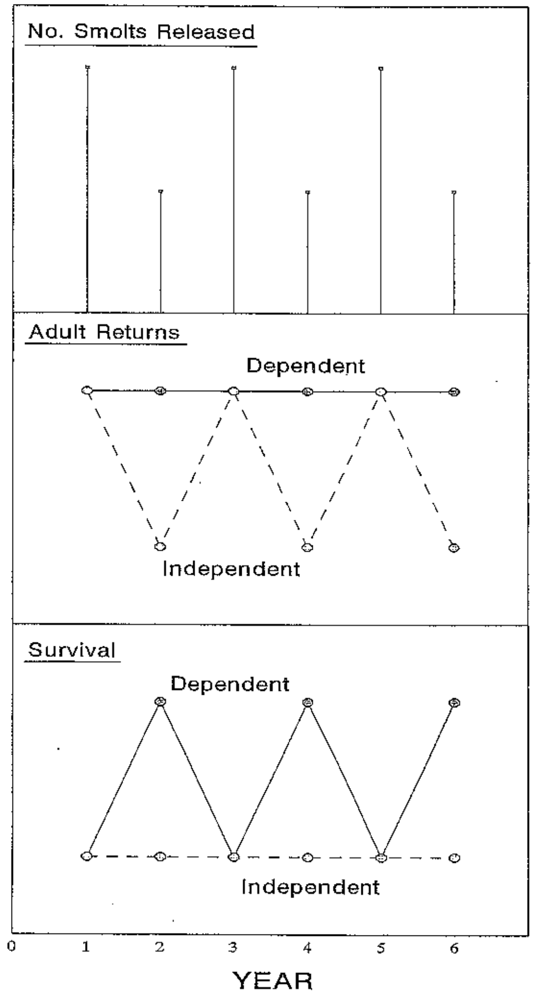

FIGURE 9.—Conceptual model of an experiment to determine if Strait of Georgia chinook or coho salmon production is limited by density-dependent interactions at sea. Number of hatchery smolts released are 100% and 50% of capacity in alternate years. If there is density dependence (solid lines) at current smolt abundance, adult returns are expected to remain relatively constant and survival rates are expected to be higher in years of low smolt numbers.

Conclusion

Hatcheries have a demonstrated capability to produce salmon. There may be concerns over marine survival rates, but the annual harvest of over 500,000 coho salmon and 100,000 chinook salmon produced in Strait of Georgia hatcheries (Table 2) is an important contribution to our fisheries. The past 20 years have seen not only growth in fish production but also a tremendous growth in knowledge, much of which is attributable to hatchery-related research and assessment studies. We have better understanding of the life history and ocean distribution of salmon stocks and of the harvest, ecological, and genetic interactions between wild and hatchery stocks. The challenge is to apply this new knowledge when making decisions on stock and harvest management objectives and on the role of hatcheries. These decisions will often be difficult.

We must also promote research that will provide further understanding, recognizing that the most valuable research is likely going to require large-scale interventions in the production of juvenile salmon with possible effects, at least in the short term, on adult returns.

Acknowledgments

I am grateful to several Canadian Department of Fisheries and Oceans staff for their assistance with this report, including C. Cross, S. Lehmann, and K. Pitre for data compilation and discussion; D. Patterson and A. Kling for preparation of figures; and V. Palermo and B. Piper for statistical analysis. L. Blankenship and W. Smoker provided helpful review of the manuscript. Thanks also to C. Walters, University of British Columbia, for stimulating discussion on several aspects of the paper.

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