A Historical Perspective on Salmonid Production from Pacific Rim Hatcheries

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INTRODUCTION

Development of the North Pacific salmonid hatchery system began in the late 19th century and has played a prominent role in enhancement of the salmonid resource in Pacific Rim nations since the 1950s. Until recently, the artificial propagation approach to enhancement of fisheries has not been seriously questioned, but the recent alarming declines in wild spawning stocks have forced a re-evaluation of industrial-scale hatchery production of north Pacific salmonids. Declines have been observed in chinook, coho, and sockeye salmon stocks in the Pacific Northwest; high harvest rates of wild fish in fisheries targeted on the more abundant hatchery stocks have continued, and high production of hatchery chum salmon in Japan and both pinks and chum salmon in Alaska, declining fish size and altered return timing and age at maturity, have raised concerns over limits on ocean carrying capacity.

In the Pacific Northwest, recent Endangered Species Act listings of Redfish Lake sockeye in the Stanley Basin of Idaho, Sacramento River winter chinook in California, and fall, summer, and spring runs of chinook in the Snake River Basin of Idaho and Oregon have focused attention not only on habitat loss and fishery-related impacts on the wild stock but on the genetic and demographic consequences of uncontrolled expansion of hatcheries as well (Meffe 1992; Nehlsen et al. 1991). Proposed recovery plans for listed Snake River chinooks and sockeye call for a limit on annual releases from Columbia Basin hatcheries to 1994 levels (Schmitten et al. 1995).

In Alaska, the hatchery successes that were hailed...
in the mid 1980s are being assailed in the 1990s. The return of record numbers of hatchery pink and chum salmon and high abundance of natural fish in the North Pacific has led to record high catches and record low revenues to fishermen, and has brought forward new criticism of hatchery management strategies. Concerns over decreasing fish size in the hatchery-based fishery for chum salmon in northern Japan has led to a decision by the Japanese government to reduce hatchery releases. Similar concerns for declining size and increasing age at maturity observed in North Pacific stocks of five salmon species suggests that large-scale hatchery production is resulting in density-dependant growth reduction (Kaeriyama and Urawa 1992; Bigler et al. 1996).

This report provides managers with an historical data set of hatchery releases from Pacific Rim nations, excluding Russia, for the six Pacific salmon species and steelhead through 1992. In addition, an analysis of survival trends for hatchery coho and fall chinook from the eastern Pacific and chum from Japan are presented.

**METHODS**

**Release Data**

Annual production rates from Pacific Rim hatcheries were obtained for six species of Pacific salmon: chinook (*Oncorhyncus tshawytscha*), coho (*O. kisutch*), sockeye (*O. nerka*), pink (*O. gorbuscha*), chum (*O. keta*), masu (*O. masu*), and steelhead trout (*O. mykiss*). We compiled this information from published and unpublished sources and organized it in a computer database. Production trends for the 40-year period from 1950-1990 were analyzed for all species from four geographic areas: Pacific Northwest (Washington, Oregon, Idaho, and California), Canada (British Columbia), Alaska, and Japan (Honshu and Hokkaido). Data from Russia and Korea were unavailable as a continuous historical series, however discontinuous data were available from three sources and were used to estimate total present Pacific Rim output (Heard 1995; Mahnken et al. 1983; Konovalov 1980).

Release data from Alaska for chum, pink, coho, sockeye, and chinook salmon were obtained through Alaska Department of Fish and Game annual reports (McNair 1996). Alaska steelhead releases were supplied by Alaska Department of Fish and Game (Marianne McNair, Alaska Department of Fish and Game, P.O. Box 25526 Juneau Alaska, Pers. commun., Oct., 1996). Release data for all species from British Columbia were provided by Canadian Fisheries and Oceans (Ted Perry, Canadian Fisheries and Oceans, 555 West Hastings Street, Vancouver, B.C., Pers. commun., Oct. 1996). Japanese release information on chum and pink salmon was supplied by the Hokkaido Salmon Hatchery (Masahide Kaeriyama and Shigihiko Urawa, Hokkaido Salmon Hatchery, 2-2 Nakanoshima, Toyohira-ku, Sapporo 062, Japan, Pers. commun., Oct., 1996).

Until recently, a consolidated data set for hatchery production has been unavailable for the western United States (Wahle and Smith 1979; Mahnken et al. 1983; Isaksson 1988). We compiled a comprehensive historical data set from previously unreported raw data forms archived by fishery agencies, annual reports of hatcheries, and electronic databases. We obtained earlier salmon release records from Oregon and Idaho and steelhead from Washington which were previously not available.

**Survival Data**

Survival information for coho and chinook salmon was obtained from coded wire tag (CWT) data bases maintained by the Pacific States Marine Fisheries Commission. The historical CWT data set was assembled by Maria Claribel Coronado-Hernandez (1995) and is contained in her doctoral dissertation. This seminal work synthesizes and analyzes, for the first time, spatial and temporal factors affecting survival of hatchery-reared chinook and coho salmon and steelhead in western North America over the time period for which coded wire tag recoveries are available (1971-1989). Release-recovery information is presented in the form of expanded CWT recoveries using only non-experimental production groups. Recoveries were standardized to the most common age at return using virtual population analysis (Coronado-Hernandez 1995).

We computed mean survival rates from this data set and used two-way analysis of variance to make statistical comparisons of mean survival values over time. We chose coho and fall chinook salmon for analysis of temporal and geographic variation because of the large data sets available for these species. Pairwise comparisons between sampling dates were made using the Fishers PLSD test. All statements about statistical comparisons are based on the P <0.05 significance level.

Survival data for Japanese chum salmon was provided by the Hokkaido Salmon Hatchery (Masahide Kaeriyama and Shigihiko Urawa, Hokkaido Salmon Hatchery, 2-2 Nakanoshima, Toyohira-ku, Sapporo 062, Japan, Pers. commun., Oct., 1996). These data were compiled through records of fishery catch and hatchery escapement to the Japanese coastal net fishery and to Hokkaido and Honshu hatcheries, respectively.
RESULTS - HISTORICAL PRODUCTION OF PACIFIC SALMON AT PACIFIC RIM HATCHERIES

Coho Salmon

Coho salmon are among the most successful of hatchery-cultivated species in the Pacific Northwest and Canada. Coho salmon hatcheries were highly successful in returning adults to the fisheries in the 1970s, when record smolt-to-adult survivals were recorded in the British Columbia and Puget Sound regions.

Coho salmon production in western North America grew slowly from its inception at the turn of the century, and before 1940 the output from hatcheries never exceeded about 25 million fish annually (Fig. 1A). The slow rate of growth can be attributed to failure of hatcheries to contribute to expansion of the fishery (McNeil and Bailey 1975). Following a period of reduced production during World War II, coho salmon hatcheries entered an industrial phase of expansion that lasted through the 1970s.

In the 1950s and 1960s, advances in the knowledge of feeds, diseases, and the early life history culture requirements of coho salmon led to improved post-release survival of hatchery fish (Lichatowich and McIntyre 1987). Coho salmon are released either as fry or as yearling smolts (25-30 g) and size at release had also been increased over the years and contributed to improved adult survival (Wahle and Smith 1979). These achievements were even more important in that they coincided with a period of rapid deterioration of freshwater habitat and blockage of major migratory pathways by hydroelectric dams. Given these successes, fishery managers came to believe that hatcheries were a means by which the Pacific Northwest could continue to develop its water resources for power, irrigation, and industrial or domestic use and at the same time, maintain fisheries at historic levels (Lichatowich and McIntyre 1987). Increased reliance on hatchery coho salmon led to the rapid expansion of production through the 1970s. In the late 1970s and early 1980s, private sea ranches added 9.3 million smolts per year to Oregon coastal production (Fig. 1A) and helped lead to a record production of 198 million hatchery coho salmon in 1981. In the years that followed however, coho salmon production in the Pacific Northwest stabilized and began to decline (Fig. 1A).

Beginning in 1989, a period of declining production began in most sectors of the coho salmon hatchery system. The decline in overall production from the contiguous western United States was partially offset by the added production of 40 million hatchery fish from Alaska and British Columbia. This decline can be attributed to various factors: Survival of adult hatchery fish declined following the oceanic regime shift in 1976 and a series of El Niños events in the late 1970s and early 1980s. These conditions resulted in reduced escapement, and hatcheries were unable to meet egg needs for full production. More restrictive inter-basin egg transfer policies were introduced to protect remaining wild populations, and reduced operating budgets at some hatcheries further reduced coho salmon production.

Chinook salmon

Like coho salmon, chinook salmon are released either as fry or as yearling smolts. Chinook salmon were the first salmon species to be artificially propagated in western North America and are artificially propagated in hatcheries along the eastern Pacific seaboard from California to Alaska. More chinook salmon have been produced from hatcheries than any other species in the Pacific Northwest. The first effort to artificially propagate chinook salmon in North America was at the Baird Fish Hatchery on the McCloud River in California in 1872. This hatchery was established to obtain chinook salmon eggs for transport to Atlantic Ocean tributaries to replace depleted Atlantic salmon (Salmo salar) runs. Today, the center of hatchery production is the Columbia River Basin where approximately 27% of world chinook salmon is produced.

Fall chinook are the most commonly cultured life history type in both British Columbia and the Pacific Northwest. Also known as "ocean-type" (Healey 1991), fall chinook salmon most frequently inhabit coastal rivers, although ocean-type fish are cultured in the Columbia River as far upstream as the Methow River. Fall chinook salmon are sometimes released as fry but are more commonly reared for three months and released at hatcheries in the spring at approximately 7-10 g. To improve survival, some hatchery populations of fall chinook are reared to yearling size and generally released in the spring at 25-30 g as age-1 smolts (Wahle and Smith 1979).

Spring and summer chinook salmon, or "stream-type" life history stocks (Healey 1991), are produced at hatcheries located primarily on large river systems of the Pacific Northwest, British Columbia, and Alaska. Spring chinook salmon are the predominant stocks produced in Alaskan hatcheries. Spring and summer stocks of chinook salmon are seldom released as underyearlings and are grown in hatcheries to the largest size, often over 100 g average, of any of the Pacific salmon species (NRC, 1995). Underyearling releases have been attempted at hatcheries where high rearing water temperatures result in accelerated growth, but survival to adult from releases of these intermediate sized fish is generally lower than those of
larger yearling fish (Zaugg et al. 1985, 1986).

Hatchery production of chinook salmon began in Washington State in 1895 at the Kalama hatchery on the Columbia River, and production grew slowly to around 50 million fish released until the late 1930's (Fig. 1B). Production dropped slightly during World War II, then accelerated following improvements in culture technology and construction of new hatcheries. The decade of 1950-1960 began the industrial phase of chinook salmon hatchery production, as development in the Pacific Northwest resulted in loss of freshwater habitat. Growth of the fisheries also added pressure to the hatchery system to increase production. New hatcheries on the middle Columbia River were constructed to mitigate for lost habitat above Grand Coulee dam and other mid-Columbia hydroelectric projects. Between 1960 and 1976, 30 hatcheries and 12 rearing ponds raised anadromous salmonids in this region (Wahle and Smith 1979). Another surge in production occurred in Puget Sound hatcheries in Washington State during the 1960s. New lower Columbia River hatcheries and growing production in other sectors of the Pacific Northwest drove annual releases to more than 300 million chinook salmon smolts by the early 1980s. Production increases from British Columbia and Alaska hatcheries in the 1980s added another 100 million fish annually. By 1988, when production peaked, more than 420 million fry, fingerling, and smolts were being released from eastern Pacific hatcheries, a seven-fold increase from the base level of 59 million fish released in 1949.

Fig. 1 Hatchery production of (A) coho salmon and (B) chinook salmon juveniles from Pacific Northwest, British Columbia, and Alaska hatcheries, 1980-1992.
Chinook salmon hatchery production began to decline in the late 1980s for the same reasons that coho salmon production is now falling.

**Chum salmon**

From the late 1880s until the recent expansion of chum salmon ranching in Japan, hatcheries released fry from rearing ponds to the stream soon after yolk sac absorption. Egg and fry development was accelerated in Hokkaido through the use of constant, 8°C ground water. These condition favored releases from early to mid-February when fry were sometimes subjected to severe conditions in the streams and coastal marine waters. With temperatures as low as 0-5°C during February and March, survival was minimal. In 1962, production-scale hatchery experiments were undertaken to delay release to a time of more favorable sea temperatures. These experiments involved feeding up to 300 million fry for short periods (Mayama 1985) and demonstrated that dry diets could increase body weight from 0.6 to 1.0 g in about one month. Fry fed on these diets could be released from Hokkaido hatcheries in May, when coastal water temperatures exceeded 10°C. These fry are usually released 50 d before average sea surface temperature reaches 15°C. Larger fish of 2-3 g average weight released to coastal waters during spring periods of high primary and secondary productivity survived at a much higher rate than smaller ones. Adult returns from unfed fry released in 1950-60 averaged 1.2%; returns improved to 2.3% after 1966 as the percentage of fed fish increased (Isaksson 1988).

Japanese chum salmon catch was high prior to World War II, but dropped during the war years. Following the war, catch increased for a few years, then decreased as stocks were overexploited. Beginning in the 1970s, catch of Asian chum salmon rose again, primarily as a result of massive Japanese hatchery releases. From 1950 until 1970 Japanese hatchery production rose from 260 million fish released to around 580 million (Fig. 2A). Following improvements in adult contribution through the release of fed fry, and the loss of foreign fishing grounds to exclusive economic zones (EEZs), the Japanese chum salmon hatchery system entered a phase of rapid industrialization. Production rose from 260 million fry released in 1970 to 2 billion released in 1981. After the early 1980s, Japanese production of chum salmon leveled off.

The Japanese hatchery system is the largest in the world in terms of fish released and returned 78 million adult fish to the Japanese coastal fisheries in 1995 (H. Urawa, pers. commun.). The Japanese land-based fishery is almost entirely hatchery-dependant; wild stocks are virtually non-existent in northern Japan. Another interesting feature of the Japanese hatchery system is that it has reduced reliance on high-seas fisheries. The imposition of foreign EEZs has restricted the Japanese high-seas fishery on chum salmon destined for Russia and North America, but the loss to the national fishery has been more than replaced by hatcheries.

In North America, enhancement efforts for chum salmon also accelerated in the 1970s, primarily in Alaska and British Columbia (Fig. 2A), adding an additional 850 million fry to the already impressive releases by Japan for a total Pacific Rim production of nearly three billion chum salmon fry (exclusive of Russian hatchery releases).

**Pink salmon**

Pink salmon are second to chum salmon in the numbers of juveniles released into the North Pacific Ocean; accounting for 29% of the total reported in 1992 (Heard 1995). Pink salmon are released from most hatcheries at 0.5-2.0 g size (Isaksson 1988). Alaska is the largest producer of pink salmon and released more than 800 million juveniles in 1992 (Heard 1995; McNair 1996). Heard (1995) also notes that Russia is the second largest producer of hatchery pinks; with 584 million juveniles released in 1992.

Pink salmon releases remained low (less than 100 million) until the early 1980s, when an industrialization period began in Alaska, and numbers of released fish from North America increased tenfold to a total of 1.006 billion in 1992 (Fig. 2B). When added to Russian production, total world production of pink salmon was 1.590 billion produced in 1992. Pink salmon is the most recent of the Pacific salmon species to be industrially produced.

**Sockeye salmon**

Sockeye salmon were propagated in Alaska before the turn of the century to enhance existing runs, and millions of eggs were sent to the Atlantic coast in an attempt to establish runs there (Roppel 1982). However, initial culture efforts in Alaska were unsuccessful, and sockeye salmon programs were discontinued early in the 20th century (Allee 1990). Similarly, 11 sockeye salmon hatcheries built in British Columbia before 1917 produced no consistent benefits, and production ceased soon thereafter (Foerster 1968). In Washington, artificial propagation of sockeye salmon began in 1896 at the Baker Lake Station in the Skagit River basin and continued until this facility was closed in 1933. In addition to supplementing the run of sockeye salmon to Baker Lake, this facility was the source for the sockeye salmon introduced into Lake Washington where a strong run was eventually established (Kemmerich 1945).
Sockeye salmon culture began in the Columbia River in the 1940s at the Leavenworth Hatchery in eastern Washington state. This production effort attempted to mitigate for losses of sockeye due to construction of hydroelectric dams on the middle Columbia River (Mullan 1986). Smolts were produced for a period of about 20 years, but disease and low returns forced abandonment of the program by the 1960s. Small smolt and fry-release programs still exist for sockeye in Puget Sound and on the Washington coast, but by and large, sockeye salmon culture in the Pacific Northwest is insignificant. Along with pink salmon, sockeye salmon production constitutes one of the smallest artificial propagation programs for any species in the Pacific Northwest. Recent attempts to reinvigorate sockeye salmon culture program in the Pacific Northwest include a combined hatchery and net-pen culture system operated by the State of Washington in Lake Wenatchee and a recovery program for the endangered Redfish Lake sockeye salmon in Idaho’s Stanley Basin (Flagg et al. 1991, 1995).

British Columbia is now by far the largest producer of artificially propagated sockeye salmon, producing more than 290 million fry in 1993 (Fig. 3A). Fry are produced in spawning channels containing gravel substrates, where returning adults spawn naturally. Fry are allowed to migrate...
volitionally out of the channels upon swimup, usually into a lake. Spawning-channel culture of sockeye salmon in British Columbia constitutes the least invasive culture technique used to mass culture Pacific salmon. These extensive artificial propagation techniques require no feed, use natural spawning substrates, and require no handling of either juveniles or adults during rearing. Although spawning-channel culture of sockeye was initiated prior to the 1950s, the program did not accelerate until the 1960s when output increased from 2 million fry in 1960 to 258 million in 1980 (Fig. 3A).

The Alaskan hatchery system is now the major producer of sockeye smolts in North America, and although a recent entrant (1974) into large-scale sockeye production, has grown rapidly and produced 75 million smolts in 1994, or 21% of total North American production (Fig. 3A). Alaska also releases age-0 sockeye after brief holding in sea-pens.

**Steelhead and masu salmon**

Hatchery steelhead are produced entirely in North America (Fig. 3B), while masu salmon are only produced in significant numbers in Japan (Fig. 4). In terms of total production, steelhead and masu salmon are minor species, but in terms of their contribution to regional fisheries, steelhead programs are important and produced an estimated 738,000 adults annually from 1978 to 1987 (Light 1989). Like coho salmon and chinook salmon, steelhead coho salmon and chinook salmon, steelhead coho salmon and chinook

![Fig. 3](image-url) Hatchery production of (A) sockeye salmon and (B) steelhead salmon juveniles from Pacific Northwest, British Columbia, and Alaska hatcheries and spawning channels, 1900-1992.
salmon, steelhead populations in Washington, Oregon, Idaho and California have experienced steep declines in abundance in recent years.

Artificial propagation programs for steelhead first appeared in the late 1800s and are presently operating throughout the Pacific coast region from Alaska to California. Coastwide releases did not exceed 5 million fish for most of the first half of the century. Releases declined during the war years but increased rapidly from 1960 to a peak production of 35 million fish released in 1985-87. There was a steep reduction in steelhead production in Washington state (Fig. 3B) following the 1977 U.S. vs. Washington court decision that established tribal treaty fishing rights, but the state resumed former levels of production in 1984. Steelhead production dropped by about 20% from 1989-1992. In 1992, more than 90% of total steelhead production was from hatcheries in the Pacific Northwest.

Unlike chum salmon in Japan, masu salmon production has actually decreased in the last two decades (Ohkuma and Nomura 1991). Masu salmon, which are highly dependent on the riverine environment for up to two years prior to outmigration to the sea and upon their early return as adults, have suffered due to degraded freshwater habitats. Channelization of stream banks with concrete and the construction of dams have damaged freshwater spawning and rearing habitat, and the practice of intercepting returning adults at the mouths of rivers for hatchery propagation has reduced the number of naturally spawning adults (Ohkuma and Nomura 1991).

No dramatic rise in production releases have occurred in the years since 1960 for which data is available. Less than 10 million fish have been released annually (Fig. 4).

Total Pacific Rim Production

Total Pacific Rim production for all species combined, excluding Russia, is given in Figure 5. Four phases in the development of the Pacific Rim hatchery system are evident: 1) a developmental period beginning in the late 1800s and ending around 1970, during which a rudimentary hatchery husbandry was developed; 2) a period from 1970 to 1980, during which significant technological improvements in feed and disease control were made and new hatcheries were constructed; 3) an industrialization period from 1980 to 1990 when intense fishing, loss of freshwater habitat, and declining ocean productivity accentuated the construction of more mitigation and enhancement hatcheries and accelerated production; and 4) a post-industrialization hatchery period where survival declined, hatchery escapement goals for adult spawners were not reached, and reduced operating budgets resulted in a decline in production of chinook and coho salmon and steelhead in the Pacific Northwest and Canada while high production in the north Pacific for chum and pink salmon reduced north Pacific for chum and pink salmon reduced
revenues to the fishermen and resulted in a leveling off or reduction of hatchery releases for chum and pink salmon. Total Pacific Rim production for all species in 1992 stood at more than 5.5 billion fry, fingerlings, and smolts released (Heard 1995).

RESULTS - TRENDS IN SURVIVAL OF HATCHERY FISH

Coho salmon

Regular CWT sampling of Alaskan coho salmon stocks began in the early 1970s. Short- and long-term trends in mean survival of hatchery coho salmon were evident for both southeast Alaska and the more northerly coastal regions. Survival of southeast Alaska hatchery stocks was much higher than that of fish from the coastal regions to the north. Southeast Alaska stocks showed two peaks in adult return: one in 1982 and another in 1988-89. Variance was highest during these peak years when mean survival exceeded 10%.

Mean survivals of hatchery coho salmon released into tributaries of British Columbia’s Strait of Georgia peaked in the early 1970s; these were the highest mean survivals (> 25%) recorded for any location within the North American range of the species (Fig. 6A). As in southeastern Alaska, variance was highest in years of high survival. Survival dropped from an average of around 20% in 1972-76 to less than 7% in the 1980s. The trend in survival since 1980 has continued downward, reaching record lows of less than 2% in 1990. Fraser River hatchery stocks, which also enter the waters of Georgia Strait after release, showed a similar declining trend and comparable low survivals in the 1980s.

A comparison of Puget Sound and Columbia River coho salmon stocks showed a similar trend of higher survival for those stocks released into coastal estuaries than those released into coastal oceanic environments (Fig. 6B). Puget Sound stocks exhibit consistently high mean survivals (7-13%) from the early 1970s through the mid 1980s, with notable declines following the 1977 and 1983 El Niños. The decline associated with the 1983 El Niño continued at least through 1990. Again, variation was highest during years of highest survival. On the other hand, Columbia River hatchery stocks exhibited mean survivals of generally less than 5% from 1972-90. Like Puget Sound stocks, declines in survival of Columbia River stocks occurred after the El Niño of 1977 and 1983, but unlike Puget Sound stocks, the general downward trend was not evident after 1983.

We noted a striking difference in survival between hatchery coho salmon stocks released into the larger, protected coastal estuaries along the eastern Pacific seaboard (southeastern Alaska, Strait of Georgia, Puget Sound) and those released directly to the ocean. Figure 6A compares survival trends in a typical estuary, for example the Strait of Georgia, with those of all coastal stocks north of the Columbia River and south of the Columbia River. Although Georgia Strait
stock survivals fluctuate widely and exhibit a severe decline in the 1980s, they remained more than twice as productive (approximately 5%) as the coastal stocks (approximately 2%) until 1987. After 1987, all stocks declined to survivals around 2%.

A comparison of bi-decadal mean survival by region revealed another interesting feature of hatchery coho salmon releases from 1970-90 (Fig. 7). When arranged in order of declining survival, general latitudinal clines appeared among the coastal stocks, both north and south from the center of the geographic distribution of the species, at about the latitude of Vancouver Island. This region had the highest survival (4%), with coastal California and coastal Alaska (at either end of the geographic range) having the lowest survivals, at 1-1.5%. Latitudinal anomalies were observed in large coastal estuaries such as the Strait of Georgia, Puget Sound, and southeast Alaska. These areas are known to be excellent areas for juvenile rearing and for survival of salmonids (Healey, 1980; Simenstead et al., 1982), with relatively high survivals of 5.5-7.5% during this period.

Fall chinook salmon

Fall chinook salmon exhibit quite different survival characteristics from coho salmon. Because of smaller size at release, survival of hatchery fall chinook salmon is less than that of coho salmon. Furthermore, survivals and trends in survival are distinctly different between fall chinook salmon hatchery stocks north of Puget Sound and those to the south (Fig. 8). Survivals peaked in Puget Sound, Strait of Georgia and outer Vancouver Island in the
Fig. 7 Mean survival of hatchery coho salmon by region, 1970-1990.

mid-1970s at between 3-4%, then declined sharply to less than 2% in the 1980s following the El Niño of 1977 (Fig. 8A). A further decline to about 0.5% survival followed the 1983 El Niño and survival has continued downward since. Stocks south of Puget Sound showed the opposite trend, with survival rates of less than 1% through 1982 rising to around 2% following the 1983 El Niño (Fig. 8B). It appears that the 1983 El Niño acted to enhance survival of southern fall chinook salmon in the mid-1980s rather than to decrease survival. However, mean survival of fall chinook salmon, aggregated by region, failed to show the same geographic cline as that of coho salmon.

Chum salmon

Survival of chum salmon released from Hokkaido hatcheries has followed a trend that appears to be less influenced by ocean conditions and more by improvements in hatchery technology (Figure 9). Survival of Hokkaido chum salmon has risen uniformly from 2.5 to 4% from 1965-1988, a period in which production increased from 550 to 970 million fry released. The number of juveniles released and their survival both increased with time. This apparent inverse density-dependant survival has been noted by McNeil (1991) who suggests that the relationship may be an artifact of improved hatchery technology, or satiation of predators at higher levels of juvenile production. However, Kaeriyama (1996) presented evidence that other life history characteristics of enhanced chum salmon, namely decreased body size and an increase of age-at-maturity may indicate the beginning of a density-dependant effect of continued large-scale releases from Japanese hatcheries.

DISCUSSION

Researchers from North America and Japan have noted the dramatic decline in salmon stock abundance and body size in the southern portion of the species range in North America. These declines have been especially apparent over the past two decades (Nehlsen et al. 1991; Bigler et al. 1996; Ricker 1981). However, while the abundance of stocks in the Pacific Northwest has declined, the abundance of populations to the north, both in Asia and North America, remain healthy and some have reached historical highs (Heard 1995; Kaeriyama and Urawa 1992; Burger and Wertheimer 1995; Zorpette 1995). Attempts have been made to assess the cause of these declines based on changes in freshwater conditions, fishing, or on variations in the marine environment (Beamish and Bouillon 1993; Cooper and Johnson 1992; Johnson 1984; Lawson 1993; Lichatowich 1993; Nickelson 1986; Northcote and Atagi 1994; Pearcy 1992; Richards and Olsen 1993; Olsen and Richards 1994;
Fig. 8 Mean survival (coded-wire tags) of fall chinook salmon released from Pacific coast hatcheries 1970-1990. (A) Puget Sound, Strait of Georgia, and outer Vancouver Island regions. (B) upper and lower Columbia River, and Washington and Oregon coastal regions. Error bars are omitted for simplicity. Asterisks denote differences (P<0.05) ANOVA, Fisher PLSD between successive means.

Fig. 9 Mean survival of chum salmon released from Japanese hatcheries in Hokkaido, 1963-1988.
Francis and Sibley 1991; Kaeriyama 1996). Most researchers have concluded that, whatever the major factor(s) affecting survival of Pacific salmonids, they are most likely to occur in the ocean environment.

Cooper and Johnson (1992), compared trends in abundance of Washington, Oregon, and British Columbia steelhead and concluded that there were similarities in trends over the entire geographic range that indicated common factors were responsible for the observed changes in survival. Because freshwater, estuarine, and nearshore conditions differ considerably from year to year within this region, they concluded that these factors alone could not explain the similarities in steelhead survivals. They suggested that similarities in steelhead abundance trends in widely separated geographical regions indicated that common factors were responsible for the observed declines, and that oceanic conditions were responsible. Olsen and Richards (1994) came to a similar conclusion while working with aggregated coastwide chinook salmon production data, namely that similar chinook salmon run-size trends can be observed between several west coast river basins, and that the data support the hypothesis that ocean conditions have had a marked and uniform impact on chinook salmon production in the Pacific Northwest. Lichatowich (1993) has pointed out that the magnitude of oceanic environmental changes and their impacts on salmon survival may be so large as to mask changes that occur in the freshwater habitat. He cautioned that this may cause managers to falsely attribute increased ocean survival to restoration effects in freshwater. Hilborn et al. (1993) further emphasizes the same point by stating that attempts to understand the impact of in-river (Columbia River) actions on survival will be confounded by changes in ocean conditions.

Coded-wire tag data shows that for the period 1970-1990, coho salmon adult survival was highest for stocks released into large coastal estuaries. Survival in these estuaries is typified by widely fluctuating mean survivals. Conversely, survival of hatchery coho salmon released into coastal regions that lack protective coastal estuaries is typified by lower, more constant survival. However, differences in survival between estuarine and coastal releases of fall chinook salmon are not as dramatic, with regions like outer Vancouver Island and coastal Oregon performing as well or better than Puget Sound and the Strait of Georgia. It is possible that such factors as size and time of entry to seawater, location and length of time in estuaries prior to outmigration, and predation may influence differences in absolute survival and temporal trends between the species.

Coho salmon survivals were depressed following the unusually strong El Niño events of the past two decades (Fig. 6) and continued to decline throughout the 1980s. Depressed survival associated with El Niño events is most evident in regions where survival has been historically high (southeast Alaska and Georgia Strait following the 1982-83 El Niño, Puget Sound following the 1976-77 El Niño). In the past 40 years, nine El Niños have affected the coastal regions of the eastern Pacific. In the 1970s and 1980s, the coastal regions of the Pacific Northwest and Canada have been beset by a series of four moderate-to-strong El Niño events, most notably the 1982-83 El Niño, which by many measures was the strongest this century. Since 1970, El Niños have occurred in 1972-73, 1976-77, 1982-83, and 1987-88.

A strong negative cline in survival of coho salmon is observed moving both north and south from the center of the species distribution in British Columbia, with stocks in western Alaska and California exhibiting the lowest survival. Fall chinook salmon, on the other hand, do not show the same strong latitudinal cline.

Fall chinook salmon survival, although apparently also affected by El Niño events, seems directed by other external factors. Stock survival north of the Columbia River peaked in the mid 1970s, while survival for regions south of the river peaked in the mid-1980s. Furthermore, mean survival of fall chinook salmon aggregated by region failed to show the same geographic cline as coho salmon. The Strait of Georgia estuary produced highest survivals, but Puget Sound fall chinook salmon did not produce higher survivals than Coastal Oregon, and produced only slightly better survival than outer Vancouver Island or coastal California. This is surprising, given the well-documented importance of estuaries for growth and survival of juvenile chinook salmon (Healey 1991; McCabe et al. 1986). Nevertheless, there is some indication that hatchery fall chinook salmon juveniles spend less time in estuaries than wild juveniles which may reduce the benefits of such areas to artificially propagated fish (Levings et al. 1986). It may be that the overall lower survival of fall chinook salmon masks regional geographic differences so evident with coho salmon.

It is tempting to postulate a cause and effect relationship between the occurrence of El Niño events and declines in survival of hatchery fish in the eastern Pacific, but no convincing ecological relationship exists. Climate conditions are known to have changed recently in the Pacific Northwest. Most Pacific salmonid stocks south of British Columbia have been affected by changes in ocean production that occurred during the 1970s. Peary (1992) and Lawson (1993) attribute this decline largely to ocean factors, but do not identify specific effects. However, given the increased frequency of El Niño events in the past two decades, and large-scale secular warming of the region (Freeland 1990), it is certainly plausible that there is at least some response to El Niño events in the form
of reduced survival of the species.

Survival of coho and chinook salmon in the southern regions may be driven by an entirely different set of regional ocean/climate conditions than those governing survival of chum, pink, and sockeye salmon; the most abundant species in the northerly regions. Two forms of decline were evident in coho salmon survival curves: sharp, short-term declines associated with El Niño events, and a more prolonged long-term decline, typical of the late 1980s, that may be related to general warming trends in Pacific waters along the eastern Pacific seaboard (Freeland 1990; Welch et al. 1995; Beamish and Bouillon 1993). Stocks released from southern regions are believed to migrate in a narrow coastal corridor that is characterized by highly variable interannual changes in flow, temperature, and current (Pearcy, 1992). Those species and stocks released into the more northerly regions enter a much larger area of acceptable ocean conditions that is greatly influenced by the Aleutian low pressure system (Beamish and Bouillon 1993).

Hatcheries have played a major role in supplying salmon and trout to the common property fishery in the Pacific Northwest. But with the near catastrophic decline in the population of southern stocks and overabundance of the northern stocks, we have entered a new era in the operation of hatcheries that cannot help but impact the traditional users of hatchery fish. The two-pronged dilemma is, how can we institute hatchery reform to both protect and recover wild/natural stocks and at the same time maintain some reasonable level of harvest for the fishers?

The present hatchery system was developed to produce an increasing supply of hatchery fish into a constant oceanic ecosystem believed to be nearly limitless in its capacity to accommodate juvenile salmonids. Until recently, these oceanic ecosystems were believed to be stable, internally regulated, and to behave in a deterministic manner. The more current view is of an open system in near constant flux—-a system without long-term stability and one that is often under the influence of stochastic factors, many originating outside the ecosystem itself (Mangel et al. 1996). The modern view of the ecosystem is one characterized by ecological uncertainty. Lack of understanding of this principle and its impact on interannual variability of salmonid abundance and survival has acted against wild fish populations through unregulated propagation and harvests of hatchery fish. Perhaps it is time for fishery managers to regulate hatchery releases to accommodate decadal-scale variation in ocean productivity.

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