CHAPTER 8. HABITAT, HARVEST, AND HATCHERIES

SOURCES OF MORTALITY AND EFFECTIVENESS OF MITIGATION ACTIVITIES

A. TRIBUTARY AND MAINSTEM HABITAT RESTORATION

In our review of habitat (Chapter 5) problems in the basin we documented that quality habitat for each life history stage is essential to conservation and enhancement of Columbia Basin salmonids. Despite extensive expenditures under the Fish and Wildlife Program and other state and federal programs, it appears there is little evidence that habitat restoration has actually improved the productive capacity of streams and rivers for salmonids (Rhodes et al., 1994).

Apparently, habitat restoration has lagged as a mitigation priority for lack of a clear understanding of the specific biophysical conditions that exemplify quality habitat. We have often heard the argument that large amounts of pristine habitat remain in the headwater reaches of the river system, especially in designated wilderness areas (see Table 8.1). However, headwater reaches are predominantly high gradient within constrained channels and are generally unproductive owing to low concentrations of plant growth nutrients. Food web fertility derived from decaying carcasses of spent adult spawners may have been an essential feature that is now missing from these reaches (Bilby et al., 1996). In some areas of the basin, habitat degradation of headwater reaches is pervasive from mining, logging and road building (see Chapter 5).

Table 8.1. Chinook salmon habitat in the Columbia River basin as length of spawning and rearing habitat accessible in kilometers. Source NPPC (1986).

Type	*Original*	*1975*	*Percent of Original*
Spring	17088	8718	49
Summer	8002	3650	54
Fall	3961	2749	31
Average			45

It is generally assumed that recent use of best management practices (e.g., selective timber harvest prescriptions, larger riparian buffer strips, better road construction and maintenance guidelines) and use of audits to enforce them has improved instream habitats in managed landscapes. However, empirical demonstrations of real influences of best management practices on habitat variables (e.g., sedimentation, temperature, riparian vegetation, woody debris) are rare in the basin (Rhodes et al., 1994). Moreover, habitat enhancement traditionally is viewed mechanistically, consisting of construction or emplacement of instream structures such as rock gardens, step weirs and log piles (Hunter, 1991). Such structures often are not effective and may wash out in floods (Frissell and Nawa, 1992).

Because of the vast spatial scale of human activities that have caused degradation of habitats in tributary streams (especially including grazing, cropland and irrigated agriculture, and logging), it is unlikely that site-specific interventions can successfully offset the adverse ecological effects of land use activities. Instead, significant modification of land use patterns and practices, which if correctly implemented could result in the re-establishment of key natural biophysical processes over large areas, will be necessary for restoration at appropriate ecological scales (Doppelt et al., 1993; Frissell, 1993; 1993; Rhodes et al., 1994). This has been termed "passive restoration" in recent discussion of ecosystem restoration (Kauffman et al., 1995). The first principle of tributary restoration is to identify and fully protect from future human disturbance existing areas where high ecological integrity and largely natural ecosystem processes persist (Reeves and Sedell, 1992; Doppelt et al., 1993; Frissell, 1993; 1993). Such areas might include intact headwater tributary catchments, as well as downstream alluvial reaches where human activities have been relatively limited in their scope and ecological effects (Doppelt et al., 1993; Frissell, 1993; 1993). The most urgent priority for active intervention is to implement selected restoration measures necessary to prevent further ecological damage in these relatively intact areas. Such interventions do not include projects intended to re-create habitat that has been destroyed, but rather to de-fuse processes of impact that discourage the natural re-development of habitat diversity (Doppelt et al., 1993; Frissell, 1993; 1993). Examples of such interventions include obliteration or hydrologic de-commissioning of existing road networks, removal and exclosure of domestic livestock from key areas, modification of irrigation practices (see Table 8.2), removal or modification of selected dams diversion structures and re-establishment of instream flows in key reaches, and perhaps re-introduction of locally-adapted propagules of native riparian plant species (e.g., willows) that have been extirpated from certain tributary drainages. Comprehensive ecological assessment is necessary to successfully identify and establish priorities (among sites and activities) for such interventions, and such assessments must be a principle objective in watershed analysis projects of state and federal agencies (Frissell and Bayles, 1996, critique of).

Table 8.2. Acres under irrigation, and acre-feet of water delivered to agricultural enterprises by the Bureau of Reclamation, Columbia River Basin (Northwest Power Planning Council 1986).

Year	*Acres*	*Acre-ft*	*Source*
1889	400000		App. D. p. 178
1900	500000		App. D. p. 178
1910	2300000		App. D. p. 178
1925	2900000		App. D. p. 178
1947	---------	2639000	App. D. p. 181
1966	6600000		App. D. p. 178
1967	---------	8385500	App. D. p. 181
1979	---------	11653000	App. D. p. 181
1980	7600000		App. D. p. 178
1981	---------	10723200	App. D. p. 181

Our normative ecosystem concept (Chapter 2) emphasizes the importance of channel to floodplain connectivity and seasonality of flooding to create and maintain habitat (Figure 8.1). Restoration and enhancement of habitat forming processes on the large flood plains that are accessible to salmonids through reregulation of flows produce flood peaks and to stabilize baseflows, elimination of pollution loads (sediments, toxic compounds) and protection of riparian vegetation from logging and grazing are key elements of the normative river (Stanford et al., *in press*). These actions contrast with current habitat projects in the FWP and are more inclusive of the processes that the fish, especially juveniles require.

In the mainstem Snake and Columbia Rivers, restoring normative habitat conditions may be more problematic than for the riverine flood plains primarily because so many reservoirs are present that riverine characteristics are largely replaced by laucustrine conditions throughout the mainstems. Freshet flows will not produce habitat within the laucustrine reaches, although high flows associated with spring runoff may be beneficial to juvenile emigration via spill over the dams. In reviewing migration behavior and mortalities (Chapters 6 - 8), the importance of pulsed releases from the dams to simulate naturalized flow dynamics and stimulate emigration after

runoff has tapered off was noted along with surface attraction coupled with spill for most effective juvenile bypass of the mainstem dams became apparent. Pulsed releases may be feasible because within the laucustrine reaches of the Columbia River shallow water habitats are limited and less influenced by volume fluctuations than riverine reaches. And, available data strongly suggests that juvenile chinook and sockeye are more likely to move donwstream in association with pulsing flows. However, uncertainty about the quality and accessibility of food webs in sustaining growth and vitality of juveniles within these mainstem reservoirs also was noted (Chapter 6), even though recent measures of mortality suggest lower values than expected for wild fall chinook passing through lower Snake River reservoirs (Muir, 1996). Additional food web research in relation to monitoring of juvenile mortalities is required to resolve normative habitat conditions in the mainstems.

Conclusions (level of proof) and recommendations

1. Habitat restoration in the normative river context has not been emphasized to date in the FWP as a primary mitigation need and it should be. (1)
2. Research to clarify habitat conditions in all of the mainstem reservoirs is needed.(1)

B. Harvest

Salmon are harvested by many different activities in the Columbia River basin. Intentional, or directed, harvest of adults and immature salmon for commercial, subsistence, ceremonial and recreational purposes has occurred since time immemorial, and records of intensive commercial harvest dating to 1865 are readily available (Craig and Hacker, 1940; Chapman et al., 1991; Chapman et al., 1994; National Marine Fisheries Service, 1995; National Research Council, 1996). Unintentional, or incidental harvest of salmon occurs in those activities which are not intended to capture the salmon species or life history stage which is taken. Incidental harvest of Columbia River salmon occurs in marine and freshwater fisheries for other species of fish, during salmon fisheries targeted on older life history stages of salmon, and in the production of electricity at hydroelectric dams, during and after logging operations, during and after irrigation withdrawals, during land development operations such as road and real estate building, and during and after some types of mining operations.

DIRECTED HARVEST

For the past several human generations, the number of salmon harvested in directed salmon fisheries has often been counted or estimated in an attempt to determine whether or not the productive capacity of the populations was being exceeded (Ricker, 1954; Beverton and Holt, 1957) and for other purposes, such as taxation. The directed harvest estimates were made because in theory, and in practice, it is possible to harvest at a rate high enough to diminish a salmon population's spawning potential and to cause it to be extirpated (Cushing, 1983). It was also assumed that the principal source of human induced mortality on salmon were the directed harvests, hence it was assumed that the health of the salmon populations could be assured through appropriate limitations on directed harvests (Mundy, 1985).

INTERACTIVE EFFECTS

In the Columbia River basin it is clear that directed harvest is only one of many sources of mortality, and it follows that all sources of mortality should be accounted for in order to permit the persistence of the salmon. In practice, all human induced mortalities are measured to the extent possible, with all remaining sources, such as predation by marine mammals, being attributed to natural mortality. Clearly traditional harvest management, which seeks only to control directed sources of fishing mortality (Ricker, 1975), is not sufficient to provide for the sustainable production of the Columbia River basin's salmon. However the principles of sustainable harvest management (Beverton and Holt, 1957; Cushing, 1983) need to be carried forward in framing a harvest management paradigm which is appropriate to the persistence of the

full diversity of species and life history types of the basin's salmon. Ricker (1958) examined the effects of a fluctuating environment (variable mortalities induced at early life stages) on the productive capabilities of fish stocks.

Ideals from traditional harvest management which need to be retained relate to protecting all identifiable populations, and accounting for all sources of fishing mortality. Specifically, the ideal of limiting fishing mortality to a level which permits persistence of the smallest identifiable stock, also called a deme or population (National Research Council, 1996), a spawning aggregate of a life history type of a species, needs to be retained. In practice, fisheries management agencies have defined stocks as some identifiable aggregate of local spawning populations. The number of populations in the pragmatic stock definitions might be more a function of logistic considerations and the amount of funding available for monitoring than of biological considerations. It is now essential that the definition of a stock consider the biological criteria engendered by Endangered Species Act definitions of stock, such as the Evolutionarily Significant Unit (ESU) (Waples, 1991; Mundy et al., 1995; National Research Council, 1996). The practice of monitoring the populations, which includes counting or estimating the harvests by each of the "fisheries," needs to be retained. The concept of “fishery” should be extended to cover both the incidental and directed removals of salmon at all life history stages.

In addition to applying the principles of traditional harvest management, understanding the interactions and dependencies between harvest, the health of habitat, and the productivities of salmon populations (Ricker, 1954) is essential to improving our abilities to identify and implement salmon restoration efforts. In examining the Columbia River Basin, habitat loss and degradation, and unlimited fishing emerge as parallel companions of the initial decline in population numbers of the principal commercial salmon species (see Chapter 5 on freshwater habitat). The evolution of harvest management protection for naturally spawning Columbia River basin salmon was restrained by increases in hatchery production during the 1960’s . The large numbers of hatchery salmon drove the public policy process to sanction intensive fisheries on mixtures of hatchery and natural salmon which obscured the downward trends in production of the natural salmon populations. In the present, continuing habitat losses combine with ineffective harvest regulation as probable causes for the continuing failure of Columbia River chinook salmon. Therefore, an effective harvest management paradigm cannot be developed outside of an ecosystem context.

OVERFISHING AND INTERACTIONS WITH HABITAT LOSS

Harvests impact salmon productivities directly by reducing the numbers in the spawning populations, and indirectly by reducing the diversity of phenotypes in the population, which impacts factors important to basic productivity, such as average number of eggs per female (Miller, 1957; Ricker, 1981; Cushing, 1983, citing Russell 1931; Beaty, 1992). Overfishing

occurs when fishing removes enough spawners from a population to cause it to decline. Overfishing reduces the production of salmon by reducing or eliminating the populations which have adapted to the habitat types and environmental conditions of the basin (Ricker, 1972; Riddell and Legget, 1981; Thorpe, 1995). As it has developed from the experience of the last three generations of fisheries scientists, and as harvest regulations increasingly reflect, management of salmon ought to protect the productive capacity of salmon runs by pursuing the reasonable and essential objective of protecting the genetic diversity of Pacific salmon populations on which production ultimately depends (Paulik, 1969; Lande and Barrowclough, 1987).

Prior to 1941, excessive harvest exploitation and widespread habitat degradation (see discussion in Chapter 5) acted synergistically to reduce abundance of Columbia River Basin salmon stocks. As early as the 1870's, there are observations consistent with overfishing of the salmon runs by the commercial fishery of the lower Columbia River, when Native American harvesters, who fished up river from the commercial fisheries, found they could no longer meet their basic subsistence needs for salmon (Simms, 1877). Seventeen years later, biologists were looking to the lower river fisheries to explain sharp declines in salmon (particularly spring chinook and sockeye) returns to the Yakima River in Washington State (McDonald 1894). Information collected from the commercial fisheries of the lower Columbia River which would have permitted a quantitative assessment of its impacts on the salmon populations of individual tributaries was not available during the time of Simms and McDonald. Putting numerical values on the roles of overfishing and habitat degradation in the decline of salmon productivity remains difficult. To do so requires estimating the mortalities in each life history stage throughout the life of the salmon cohort. Unfortunately, even now we have the capability to do this for only a relatively few life history types of only a few species, such as fall chinook.

As late as 1936, salmon fisheries were an important part of the economy of the region, employing 3,820 harvesters, and generating $10 million annually for the regional economy (Craig, 1899). Although Craig and Hacker (1940) recognized that preventing overfishing was important, the authors emphasized that maintaining suitable spawning and nursery grounds was of paramount importance to the success of salmon fishing in achieving conservation. Craig and Hacker discuss in detail human population growth, logging, mining, hydroelectric power, and flood control and navigation as causes for the decline in salmon resources during the nineteenth and early twentieth centuries.

With regard to factors contributing to the first major Columbia River chinook salmon harvest declines from 1884 to 1889, Craig and Hacker cite the reduction of late spring and early summer chinook by fishing, and reductions in fishing effort as a result of falling demand for the relatively highly priced Columbia River salmon. They also note that species identification of the

early landings was not particularly accurate, which opens the possibility that the largest reported landing of Columbia chinook in 1883 could have included species other than chinook.

A contemporary of Craig and Hacker, Willis Rich (1941), linked habitat declines to fishing pressure as a source of decline,

> *"The way in which the Chinook salmon runs have held up under the excessive exploitation and a constant reduction in the available spawning area is remarkable."* (p. 429).

In the same paper Rich issued a prophetic warning to fishermen, laymen and administrators about the futility of trying to replace lost salmon spawning and rearing habitats with hatcheries.

Other contemporaries of Craig and Hacker also recognized the interaction between habitat loss and the effects of fishing in determining salmon population size. Johnson et al. (1948) stated with regard to Columbia River blueback (sockeye) salmon,

> *"The blueback is ... in an advanced stage of depletion. ... A very intense fishery, coupled with elimination of the majority of the important spawning grounds, has reduced the populations to a fraction of their former abundance."* (p. 16).

Johnson et al. (1948) did not express concern about trends in escapement of chinook as of 1935. Such concerns emerged in the literature during the 1950s, especially with respect to spring chinook (Thompson, 1951).

Since the time of Craig and Hacker (1940), a number of authorities have concluded that overfishing was a factor in the decline of Columbia River chinook. William Francis Thompson documented declines in nominal landings per unit effort of spring and summer chinook between 1876 and 1919 that were clearly associated with declines in actual chinook population size (Thompson, 1951). In a comprehensive review of the historical evidence for overfishing of Columbia River salmon, Chapman (1986) joined Thompson in concluding that overfishing was a factor in the decline of chinook.

Historian Anthony Netboy (1974) reported that the chinook salmon runs of the Columbia River were overfished, and in radical decline, after 1885 (pp. 282-283). In addition, Netboy recognized the role of habitat loses in salmon declines by citing the U.S. Army Corps of Engineers "308 Report" of 1948 which documented the existence of over 300 dams of all types in the Columbia River basin at that time (p. 285).

After 1941, the negative impact of fishing on Columbia River chinook salmon appears to be well grounded in observation. For example, Van Hyning (1973) documented the increase of ocean fishing as the main contributor to the decline of Columbia River fall chinook, 1938 - 1959. By this time, fall chinook were the dominant race of chinook in the Columbia River drainages, runs of spring and summer chinook having been reduced in abundance over the preceding 70+ years. The ocean fishery clearly had a negative effect on run sizes during the period of Van

Hyning's data base. It is noteworthy that Van Hyning's analysis included indirect measures of the effects of habitat degradation, in addition to measures of landings and fishing effort.

In order to summarize the history of the rise and fall of Columbia River basin chinook salmon fishery, the five year moving average of the annual landings is used to remove the short term noise in order to make the trends easy to see (Figure 8.2). There are five eras with starting years of 1866, 1884, 1921, 1932 and 1953. From its inception to about 1883, the fishery was reaping the benefits of harvesting relatively lightly exploited populations of chinook salmon. Although Craig and Hacker (1940) estimated annual aboriginal harvest at 18.2 million pounds of chinook (about 900,000 individuals), and while other sources have estimated higher levels of aboriginal salmon harvests (Schalk, 1986), many of the aboriginal peoples had perished in epidemics prior to the growth of the commercial fisheries.

As an apparent response to exploitation, the decline of the populations to lower levels during the second era starting about 1884 appears also to have also coincided with declining salmon markets, reduced fishing effort, and substantial loss and degradation of spawning and rearing habitat. Annual landings during the last five years of this era were on the order of 1.5 - 2 million chinook, using a nominal average weight of 9.1 kg (20 lbs) per chinook . Note that Chapman (1986) used 10.45 kg for spring/summer chinook. Since the historical landings are reported in pounds, 9.1 kg per chinook was chosen for convenience in converting number of pounds to number of individuals. From 1884 until the end of the second era in 1920, the fishery was working at an apparent annual equilibrium landings level on the order of 1.25 million chinook. Although the total chinook landings oscillated about 1.25 million individuals, the stock composition of the landings was changing, with availability of spring and summer runs declining, and exploitation of fall chinook increasing to make up the difference (W.F. Thompson in Chapman 1986).

The economics of World War I set in motion the events that closed out the second era with an increase in fishing effort both in the river, in the mouth of the river, and on the ocean (Craig and Hacker 1940). Increased demand for salmon products resulted in the final peak of the fishery. The year 1921, as fixed by the point where the five-year moving average of chinook landings last dropped below an annual harvest of 30 million pounds (1.5 million chinook, estimated), clearly marked the point where the Columbia River basin chinook populations started the slide toward extirpation, because it was at this point that the sum of the effects of accelerating habitat loss and degradation and ineffective harvest management regimes had converged to drive salmon population numbers below the critical point where they would have been able to replace their numbers from one generation to the next. Trends in marine productivity may have also been a factor exacerbating the effects of habitat loss and overfishing (Ware and Thompson, 1991).

For the next three eras, from 1921 through the present, it is likely that overfishing joined forces with rapidly accelerating habitat degradation to cause lasting reductions in chinook population levels (Craig and Hacker 1940; Rich 1941; Van Hyning 1973). During the third era, 1921 - 1931, Columbia River chinook landings experienced a decline as sharp as that marking the beginning of the second era in 1884. The decline in landings in the third era is apparently related to decreased productive capacity of the populations, since there also appears to have been an increase in fishing effort during this time period (Craig and Hacker 1940). The five-year moving average of landings crossed the 20 million pound (1 million chinook, estimated) level at the beginning of the fourth era in 1932, a year which also witnessed the beginning of development of large hydroelectric dams in the main Columbia River. The first surge of big river dam building on the Columbia during this era brought operations at Rock Island in 1933, Bonneville in 1938, and Grand Coulee in 1941. Given the evidence of fishing being a primary factor in the decline of fall chinook salmon runs beginning in 1938 (Van Hyning 1973), the combination of big river hydroelectric development and fishing pressure led to the third collapse of chinook landings starting about 1941 (Figure 8.2).

In the year when McNary Dam went into operation on the Columbia River, 1953, at the start of the current, and fifth era, the five-year moving average chinook landings crossed the ten million pound mark (500,000 chinook, estimated), not to return to date. Although the Columbia River harvest of chinook in 1988 was 10.54 million pounds (489,000 chinook, actual), the five-year moving average was held down by the lower landing figures before and after 1988. The current era has seen most of the big river dam construction, with 15 dams being built on the Columbia and Snake Rivers from 1953 - 1975, a 500 percent numerical increase over the preceding era. Chinook salmon production during the current era would have probably fallen even more precipitously if salmon produced in hatcheries had not increased sharply after World War II, when a large number of federal and non-federal mitigative programs came into being.

WHY HARVEST CONTROLS HAVE FAILED TO REVERSE DECLINES IN SALMON RUNS

Harvest management of Columbia River chinook populations remains ineffective because the two principal harvest control entities do not provide harvest regulations which explicitly provide for salmon spawning escapements to individual tributaries, i.e. they do not manage according to the productive capacities of the individual stocks (Paulik, 1969). Salmon harvest regulations under the Columbia River Fisheries Management Plan (United States Federal District Court, Portland, Oregon), as implemented by state and tribal fisheries managers, and as coordinated by the Pacific Fishery Management Council (PFMC, Portland, Oregon; PFMC 1996) PFMC, Review of 1995 Ocean Salmon Fisheries Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, Oregon and Pacific Salmon Commission (Jensen, 1986, also

CTC 1993) provide for aggregated spawning escapements to large river counting sites , such as hydroelectric dams, not to tributary spawning grounds (PFMC 1996). The harvest management of Columbia River chinook salmon under the coordinating entities, the PFMC and the PSC, has two fundamental shortcomings relative to salmon recovery efforts. One, with the exception of one natural spawning population, the impacts of PSC and PFMC harvests on naturally spawning Columbia River basin salmon stocks are not directly measured, and two, PSC harvest regulations are based on statistics derived from the number of salmon landed, and not on the numbers actually caught, so the magnitude of ocean fishery impacts on salmon stocks of concern remains obscure. Note that the comments on PSC fisheries offered here do not apply to those salmon fisheries under the jurisdiction of the Fraser River Panel, which is a distinctly different management regime.

Many salmon hatchery stocks, and the naturally spawning Columbia River Hanford Reach fall chinook, are tagged as juveniles with coded wire and fin clipped so that they can be identified in samples of fishery landings. Although hatchery stocks may be appropriate biological entities from which to infer the impacts of PSC fisheries on some naturally spawning populations, it seems unlikely that hatchery salmon stocks can be valid proxies for each and every natural salmon population of concern. For example, annual variations in oceanic distribution and migratory timings of life history stages are but two attributes for which differences between hatchery and natural populations could render any indices of fishing mortality, which are based on hatchery populations, invalid for naturally spawning populations. Further, even for a population which is tagged, if the life cycle is such that the landings of the individuals of legal size are out of proportion to the actual catches of the population, then the indices of fishing mortality will also be invalid.

The second shortcoming, the disparity between catch and landings in the PSC salmon fisheries and PFMC non-PSC salmon and groundfish fisheries, (Table 8.3), is relevant to the Columbia River salmon recovery because catch and bycatch of Columbia River chinook salmon populations in PSC and PFMC fisheries is not being estimated. Catch is a measure of the number of salmon actually killed, whereas landings measure the number of salmon actually kept on the vessel. Landings is a fraction of the number of fish killed in any fishery, and the difference between catch and landings is called bycatch, or incidental mortality. In the PSC hook and line fisheries, a regulation requires the release of fish under a minimum size limit (shakers), and in some hook and line and net fisheries, no chinook salmon of any size are allowed to be retained (chinook non-retention, legal sized and sublegal sized; Table 8.3). Not all of the fish so released are expected to live, so the reported number of salmon landed is necessarily an underestimate of the number of salmon actually killed.

Table 8.3. Annual estimates of total landings, incidental catch by fishery category; shaker, legal, sublegal, total catch, total incidental catch, total incidental catch per total landing, I/L, and percent of incidental catch in the total catch, of number of chinook salmon in adult equivalents, for all Pacific Salmon Commission fisheries, 1979 - 1992.

	Type of Fishery							
	Retention	Non-Retention				Incidental Mortality		
Year	Landed	Shaker	Legal	Sublegal	Catch	Incident	Index I/L	Percent
1979	2365600	301995	0	0	2667595	301995	0.127661	11.32
1980	2251730	294866	0	0	2546596	294866	0.130951	11.58
1981	2189445	303828	4076	3032	2500381	310936	0.142016	12.44
1982	2287289	368901	23770	18315	2698275	410986	0.179683	15.23
1983	2205210	352261	29489	22839	2609799	404589	0.183470	15.50
1984	2186297	337119	31160	23640	2578216	391919	0.179262	15.20
1985	1851845	233542	41140	57518	2184045	332200	0.179389	15.21
1986	1926438	276115	27723	35470	2265746	339308	0.176132	14.98
1987	2050465	304586	57044	62858	2474953	424488	0.207020	17.15
1988	2114972	291768	34880	66431	2508051	393079	0.185855	15.67
1989	1741698	274492	42939	50345	2109474	367776	0.211159	17.43
1990	1740361	300181	36512	52113	2129167	388806	0.223405	18.26
1991	1584825	314182	49235	61889	2010131	425306	0.268361	21.16
1992	1583080	358163	62216	70382	2073841	490761	0.310004	23.66

Source: Computed from data on pages K-1 through K-14 of the Pacific Salmon Commission Joint Chinook Technical Committee 1992 Annual Report. Report TCCHINOOK (93)-2, Pacific Salmon Commission, Vancouver, Canada.

To appreciate the magnitude of the potential impacts of ocean fisheries on salmon stocks of concern, and the disparities between catch and landings, some estimates are available from the 1992 report of the PSC Joint Chinook Technical Committee are useful. For example, in 1992 it is estimated that the PSC sports fishery in the Strait of Georgia caught the equivalent of 233,509 adult chinook salmon, however the number reported landed for this fishery, also in adult equivalents, was 126,922 (CTC 1993). Also in 1992, the PSC chinook troll fishery in Southeast

Alaska reported landing the equivalent of 142,076 adult chinook, however the total catch in this fishery was estimated to be the equivalent of 276,310 adult chinook (CTC 1993). Note that the disparity between annual catch and landings figures will vary by fishery due to changes in the number of small salmon available to be caught. In the aggregate, annual incidental harvests of chinook in PSC chinook salmon fisheries in 1979 - 1992 ran from 294,866 to 490,761 which represented incidental harvests of 11 to 24 percent of total catch, with ratios of landings to incidental harvest ranging from approximately 9:1 to 3:1, as measured in adult equivalents. The 1979 - 1992 time trend in percent incidentally harvested chinook in PSC fisheries is decidedly positive.

Although Columbia River stream type chinook (spring chinook and Snake River summer chinook) are only a very small proportion of PSC chinook landings based on recoveries of coded wire tags applied to hatchery populations, the proportion of these populations represented in the PSC chinook catch is unknown, as a matter of fact, as is also the case for non-PSC fisheries under the PFMC. Measurements of the stock composition by fishery of the PSC and PFMC chinook catches have not been taken. Juvenile chinook salmon, including spring chinook salmon originating in the Columbia River basin, are known from tagging studies to be available for harvest in the areas of some of the present PSC fisheries. Given that the combined Canadian and United States PSC fisheries caught, but did not land, the equivalent of at least 294,866 to as many as 490,761 adult chinook between 1979 and 1992 (Table 8.3), if the Columbia River stream type chinook constitute even 0.5 percent of these incidental harvests, the annual loss in adult equivalents to the Columbia River basin would be 1,500 to 3,000. Any such estimate of actual impacts of PSC fisheries on Columbia River stream type adult returns is necessarily speculative, due to the lack of stock composition data, and the impact of each fishery could be expected to vary substantially. The salmon bycatch in PFMC fisheries beyond the jurisdiction of the PSC for salmon and groundfish would add to the potential impacts of ocean fisheries on Columbia River which are not presently being addressed by assessment programs. However, given only the estimated magnitude of PSC incidental chinook harvests, the lack of stock composition information is a matter of serious concern to recovery of these types of salmon in the Columbia River basin .

CONCLUSIONS FOR HARVEST

Based on the preponderance of evidence and experience of the past one hundred years, the key points relevant to understanding the relationship among harvest, habitat, and salmon productivity are as follows.

1. Harvest management played a role in the decline and extirpation of Pacific salmon populations. Unlimited exploitation of salmon contributed to reductions in the production of salmon in the Columbia River Basin.

2. Traditional harvest management, through imposition of limits on exploitation in directed salmon fisheries, has not been sufficient to allow salmon populations of the Columbia River to persist.

3. Traditional harvest management actions will not compensate for losses due to human activities other than directed harvest because estimates of salmon production from habitats which are constantly declining in productivity will always be too high. Overfishing results when estimates of harvestable surplus are too high. A new harvest management paradigm is needed which will take habitat productivity into account.

A PACIFIC SALMON HARVEST MANAGEMENT PARADIGM

The limits on salmon exploitation rates appropriate to conservation are ultimately dependent on the productive capacity of the habitat from which the populations originate, and on objectives for the magnitude and geographic distribution of spawners. Hence, salmon harvest managers need to look at the effects of degradation of the habitat on which spawners and juveniles depend for survival. The long-term persistence of all species of salmon throughout their ranges is dependent on the implementation of a salmon harvest management paradigm which applies exploitation rates consistent with the status of the salmon bearing ecosystems (i.e., production capability).

When combined with explicit recognition of the role of habitat in determining salmon productivity, the basic approaches to harvest regimes of the salmon fisheries of the Fraser River, Canada (Roos, 1991) and Bristol Bay, Alaska (Mundy and Mathisen, 1981; Eggers, 1992) serve as the entry point to the paradigm. The effective harvest management paradigm for Pacific salmon may be defined in terms of its objectives and the information necessary to attain those objectives. Effective harvest management in an ecosystem context needs to retain some of the same

objectives of traditional single species harvest management, such as conservation of population size, public safety, and product quality (Mundy, 1985). In addition, the measure of performance for conservation needs to be extended beyond traditional measures of success, such as sustainable yield for a population of a single species, to include measures of ecological diversity (Pielou, 1969) and of ecological processes (Mathisen, 1972; Kyle et al., 1988).

The minimum information necessary to achieve these objectives under effective Pacific salmon harvest management (Fried and Yuen, 1987; Hilborn, 1987; Walters and Collie, 1988; Eggers, 1992; McAllister and Peterson, 1992) go well beyond the information required to achieve these objectives under the old single species management. Information requirements are more intensive because the assumptions permitted by productive, stable habitat are no longer valid, because the sources of mortality are numerous, and because harvests are often not identified as such. In this paradigm, the inadvertent taking of salmon by humans is recognized as incidental harvest. Salmon are inadvertently taken by other human activities during the course of the salmon's life cycle, by activities such as logging, road building, agricultural cultivation and irrigation, many kinds of pollution, hydroelectric power generation, fishing for other species, and by directed fishing for the same, and for other life cycle stages of salmon.

The concept of stock-recruitment which holds that future spawning stock size is to some extent dependent on present spawning stock size (Ricker, 1954; Cushing, 1983; Walters, 1986; Hilborn and Walters, 1992) needs to be enlarged to include other indicators of the status of the ecosystem (Ricker, 1958). Although the relation between present and future spawning stock size can be highly variable for healthy salmon populations, the understanding physical limits on future population growth posed by the number of eggs per female becomes extremely critical at the low population sizes common to salmon in the contiguous United States. Enlarging this concept will require new models to be developed which explicitly incorporate the role of habitat in determining salmon productivity. It is essential for harvest managers to find ways to establish salmon spawning escapements objectives for a watershed based on analyses of watershed attributes in addition to historical time series of the numbers of salmon spawning in the watershed. The parameters of a stock-recruitment function appropriate to effective harvest management in an ecosystem context should include information on habitat quality and quantity. Quantitative data on riparian vegetation and stream bed condition in relation to surveys of spawning adults and rearing juveniles are generally lacking.. Such information can be drawn from functions of the density and species composition of riparian vegetation, the percent of fine sediment in the spawning substrate, the abundance of critical life history stages of at least one prey, and one predator, species, and the abundance of one species utilized as an alternative by the salmon's predators. If it is possible to explicitly include one, or more, of the preceding habitat variables in the salmon stock-recruitment function, it would remind harvest managers of salmon originating

from areas of high human population density of the ephemeral nature of the productive capacity of the environment.

Effective harvest management must be transboundary in scope in order to sustain Pacific salmon and their ecosystems indefinitely. Columbia River chinook salmon, along with most other Pacific salmon populations, migrate through a range of harvest management regimes of differing capabilities in the course of their life cycles. Obviously having effective harvest management regimes in only those areas close to the spawning grounds is only likely to prevent extirpation in those cases where the spawning and rearing areas, as well as the migratory corridors, remain relatively pristine. In those cases where stocks from damaged freshwater habitats interact extensively with ineffective harvest management regimes, extirpation seems likely. The Pacific Salmon Treaty (Jensen, 1986), and its predecessor, the International Pacific Salmon Fisheries Commission (Roos 1991), embody the principles, if not always the practice, of international cooperation in management for salmon conservation.

Effective harvest management requires interdisciplinary staffing beyond the disciplines of the biology of fishes and mathematics ordinarily found in the old single species harvest management. It is essential to develop, *" ... a framework for integrating predictable and observable features of flowing water systems with the physical-geomorphologic environment."* (Vannote et al., 1980, p. 135). The hydrology and geomorphology of the watersheds, as well as the consequences of riparian vegetation for salmon production, needs to be a part of Pacific salmon harvest management for salmon originating in all types of habitats. It is especially important for conservation of stocks originating from damaged habitat. As Willis Rich (1941), Joseph Craig, and Robert Hacker (1940) wrote more than half a century ago, understanding habitat is essential to sustainable salmon production.

EFFECTIVE HARVEST MANAGEMENT

The quantitative attributes of effective harvest management are escapement goals, geographic gradients in fishing mortalities, and zero-sum mortality allocation. Where there are effective management strategies, they are designed to provide adequate spawning escapements to all spawning grounds, and to accurately measure the attainment of these goals on an annual basis. Without monitoring, there is no effective harvest management of salmon, because salmon harvest management depends upon information (Walters, 1986). Escapement goals under effective harvest management are quantifiable objectives, by locality and life history type, for spawning numbers, habitat, and associated species. Escapement goals must be accompanied by monitoring programs in order to be meaningful.

The concept that fishing mortalities need to decrease (be more conservative) as distance from the spawning grounds increases is essential to reduce the risk of extirpation for salmon

populations originating in damaged habitat. The farther that harvest occurs from the spawning grounds, the less likely accurate stock identification becomes, and the lower the likelihood that effective harvest management can be achieved. Put another way, ineffectively managed fisheries should be low impact fisheries. The concept that the magnitude of salmon fishing mortality should be inversely proportional to the distance of harvest from the spawning grounds is an especially critical concept at places where distant mixed stock fisheries harvest populations from damaged habitat.

The concept of zero-sum mortality allocation holds that when one source of mortality increases, some other source of mortality must decrease in order to keep the population size from decreasing. Implementation of the zero-sum principle requires that survival be measured at each stage of the life history, that survivals be held to the standard in each life history stanza, and that controls be implemented on those sources of mortality that are controllable. A basic law of biology which is determined by the number of eggs per female among other physical and biological constraints , is that each Pacific salmon population can bear only a certain average total mortality before it starts to decline (e.g. Ricker 1954). As a conservative approximation, if the five year average total annual mortality from egg to spawner for a chinook salmon population reaches the level where one female chinook cannot be expected to produce two spawners in the next generation, the population will necessarily decline. When a population is in decline, the probability of extinction is 100 percent if the decline does not stop (Rieman and McIntyre, 1993). For populations at critically low levels, such as those on the threatened or endangered species lists, when natural mortalities increase, anthropogenic mortalities need to decrease, and if they do not, the population will be extirpated.

Finally, harvest management cannot be effective unless there are consequences for the humans involved in salmon-consuming activities when survival standards and escapement goals for salmon are not met. Both Bristol Bay, Alaska, and the Fraser River, Canada, support thriving sockeye salmon populations today, because, since implementation of effective harvest management regimes, whenever spawning populations have reached critically low levels, fishing has been reduced, or stopped. For example, harvesters and processors in Bristol Bay lost an entire year's income in 1973 when biologists allocated nearly all of the adult return of 2.3 million sockeye to the spawning escapements. The sacrifice of the harvesters in 1973 led to large returns in the form of the sockeye migrations in the next generation in 1978.

In the Columbia River basin by contrast, when the El Nino phenomenon reduces ocean productivity and drought reduces freshwater survival, it is business as usual for the hydroelectric system, the commercial barge transportation system, the irrigation systems, the timber industry, and for other sectors of the economy that cause mortalities to salmon as they operate. Until there are direct consequences to sectors of the economy in addition to harvesters when salmon

populations dwindle, it is unlikely that the wide scale geographic effort necessary to prevent salmon from being extirpated can be mounted.

MIXED STOCK FISHERIES

In the face of mounting losses of Pacific salmon populations (Nehlsen et al., 1991; FEMAT (Forest Ecosystem Management Assessment Team), 1993), fisheries for mixtures of salmon stocks could be curtailed or eliminated in an attempt to protect damaged salmon populations, including federally threatened or endangered species (see PFMC 1996). Widespread losses of fishing opportunities might be necessary, if it is possible to identify and define successful concepts and approaches to sustainable salmon harvest management of mixed stocks salmon fisheries. Such concepts and approaches are termed effective harvest management. The effective harvest management paradigm is distinctly different from the historical practice of salmon harvest management, yet it retains some familiar tenets. Scientific evidence and analysis support both the old and the effective paradigms, and both effective and historical approaches are based on the concept of sustainable yield. The effective paradigm differs sharply from the old in its criteria of success, in its objectives, and in the level of detail required in the scientific evidence and analysis on which its harvest actions are based.

Sustainable yield, or catch, is the idea that properly managed salmon populations can provide a harvest benefit to humans in perpetuity (Petersen 1894, Baranov 1918, Lotka 1925, Russell 1931, Ricker 1954, Beverton and Holt 1956, Garrod 1967, Cushing 1981, Roedel 1975). The meaning of "properly managed" is at the heart of the differences between the old and the effective salmon harvest management paradigms. In the effective paradigm, proper salmon harvest management means carefully defining yield to include, as harvest, all sources of human removals of salmon, wherever, and whenever, such harvests may occur. Under effective salmon harvest management, accounting for the actual yield from each stock would require not only counting the numbers caught in all directed, or intentional, salmon harvests from a population, as was often the case in the old salmon harvest management, but it also requires an accounting of incidental, or unintentional, harvest of the population. While most salmon harvest management regimes attempt to do such an accounting, few have achieved success at the level of resolution required for protection of damaged salmon populations. For example, although hydroelectric system mortalities of Columbia River chinook are accounted for in management models along with the effects of many other factors, in the past these effects were lumped into a single value called "natural mortality." Without explicit measurement and recognition of the relative magnitudes of controllable anthropogenic mortalities, management is unable to distinguish controllable effects from the effects of uncontrollable agents of mortality which are truly natural,

such as El Nino. Note that such accounting for harvests in effective salmon management practice need not require an exact count, or even a very precise estimate, of removals, in order to be useful to salmon harvest management decisions. For example, in responding to a conservation emergency, simply being able to identify sources of mortality which may be under human control is very useful information, even when precise estimates of the magnitudes of these may be lacking or difficult and expensive to obtain (*see* (National Research Council, 1996)).

Approaches to management of mixed stock fisheries differ sharply between the old and the modern salmon harvest management. Since the "where" and "when" of salmon harvests could potentially span the thousands of miles of fresh and salt waters encompassed by the salmon's migrations, the modern concepts of how to achieve sustainability in salmon conflict sharply with the historical practice of uninformed mixed stock fishing. Mixed stock fishing occurs in areas where mixtures of fish populations, known as stocks, are harvested at the same time. Under uninformed mixed stock salmon fishing, the consequences of harvest to the sustainability of yield are unknown, and harvest management for sustained yield cannot properly be said to be occurring (Mundy 1985). Only when the annual yield, or catch, can be added to the spawning escapements, and the ages of the salmon estimated, can effective salmon harvest management attempt to achieve conservation objectives for salmon stocks. Without stock-specific catch, escapement, and age data, the salmon manager has no idea of the effect of the fishery on sustainability of the salmon populations in the fishery.

Nearly all directed salmon fisheries occur in areas where stocks are mixed to some degree, because harvest or capture takes place before the salmon reach their spawning grounds. Only on the spawning grounds are all the salmon populations clearly separated, consequently both the old and effective salmon harvest management must deal with mixed stock fisheries issues.

The effective approach to implementing modern sustained yield salmon management is informed mixed stock fishing. Informed mixed stock fishing uses information about migratory pathways, migratory timing of different populations, and other differences among salmon populations to determine the impact of fishing on the individual stocks. In an informed mixed stock fishery, catches taken in mixed stock areas can be assigned to their stock of origin in a process known as stock separation. Ideally, stock separation is quantitative with proportions of each stock in the harvest being estimated. In cases when only presence or absence of a stock in the harvest of a locality can be determined reliably, stock identification can still serve a useful purpose by determining whether fishing at that locality needs to be prohibited in the interest of protecting the stock whose presence has been ascertained.

Stock identification of catches has long been recognized by salmon managers as essential to determining impacts of salmon fisheries on stocks. As developed under conventional concepts

of sustainable yield, it is assumed, as an ideal, that a fish population can be kept at a level of escapement through controlled harvests which, on average, produce the best long-term average production by the population. This is the theory as it applies for a single identifiable stock, which is essentially a Mendelian population, or a deme (National Research Council, 1996). However, in mixed harvest situations, the question of sustainable yield becomes more complex because stock identification is needed to distinguish among salmon stocks of differing productive capacities of in the mixed stock harvest.

The importance of informed mixed stock harvest to both long term productivity and genetic diversity of salmon has long been established in the scientific literature. In addressing the consequences to long-term conservation of mixed stock salmon fisheries, Paulik et al. (1969) wrote;

> *It is also apparent that different management strategies which result in similar sustained yields may have markedly different effects on the relative abundance of the individual stocks making up the total run of the fishery. Under such circumstances the desirability of preserving a broad genetic level of response to environmental change within a salmon run might mitigate against the application of those strategies which over-exploit small stocks to the level of extinction.* (pp. 2535-2536).

Consequently, when a mixture of stocks is harvested at a common rate which permits them all to survive indefinitely, the sustainable yield is always lower, sometimes much lower, than the sum of the individual sustainable yields of the stocks, if harvested separately at rates appropriate to their individual productivities (Ricker, 1954; Paulik, 1969; Ricker, 1973). Correspondingly, the actual spawning population level, or escapement goal, which provides the greatest sustainable yield from a mixture of stocks is not the escapement goal which gives the theoretical maximum sustained yield from each stock from the mixture. This is because, in salmon management, yield, or catch, when subtracted from the total number of salmon transiting the harvest area equals escapement (Mundy 1985). Constraining harvest by the exploitation rate which permits each stock in the mixture to survive and produce could result in rates of escapement for the most productive stock that are higher than would be considered appropriate to maximize its yield.

When the preceding general principles of population biology are applied to salmon harvest management, it becomes very clear why informed mixed stock harvest is an essential part of the effective management paradigm. In mixed stock salmon fisheries, each identifiable collection of spawners from a watershed, called a stock, may have a different level of maximum sustained yield, due to differences in biological factors such as the number of eggs per female, the average size of the eggs produced, and the critical qualities of the spawning, rearing and migratory environments.

Within species of salmon there are differences in MSY for stocks, even if all the biological factors which determine productivity for each stock are the same. For example, sockeye salmon stocks coming from two lakes identical in every way, except that one is smaller than the other, will have different MSY harvest levels. This is true because the population level at which the number of successful offspring per female is the highest is about one-half the carrying capacity of the environment. Populations of sockeye from lakes will have larger values of MSY than will smaller lakes of the same productivity. In general, big environment means big MSY, and conversely, all other factors being equal.

All existing salmon escapement goals are likely to be based on data collected from mixtures of stocks (see PFMC 1996), so the escapement goal and the corresponding levels of allowable harvest depend on which stocks have been considered to be part of the mixture. For most salmon management agencies, the most economically prominent group of fish stocks were the stocks most often included in the mixture that subsequently defined MSY and escapement goals. Disaggregation of escapement goals to something approaching the watershed level may be necessary to support efforts to increase productivities of salmon populations, to enhance salmon life history diversity, and to broaden the geographic distribution of salmon in the Columbia River basin.

Informed Mix Stock Fishing

The scientific principles which form the basis for the concept of informed mixed stock harvest has been developing in the fisheries literature for more than a century, although its specific application to salmon is somewhat younger (see Roos 1991). This literature makes it clear that accounting for sources of removals, or mortalities, is absolutely essential to effective fisheries management (Petersen 1894, Baranov 1918, Lotka 1925, Russell 1931, Ricker 1954, Beverton and Holt 1956, Garrod 1967, Cushing 1981, Hilborn and Walters 1992). Without an accounting of all sources of mortality potentially under human control, the managers do not have a full range of options available to them when trying to implement conservation measures.

Accounting for all sources of mortality, in addition to directed harvest, is an extremely important part of informed mixed stock harvest. For example, not all fish caught (the catches) are necessarily landed and reported (the landings). Consequently, landings may be only a fraction of the number of salmon actually killed in a fishery. Informed mixed stock fishing requires stock composition information on catch, as well as on landings.

Informed mixed stock harvest has long been accepted in salmon management (see Roos 1991). Accordingly, the history of exploitation of salmon fisheries has been one of seeking increasingly detailed stock composition information on all species of salmon through a variety of means including visible tags (Gilbert and Rich 1925, Aro et al. 1971, Aro 1972, Gray et al. 1978,

Meyer 1983, Brannian 1984, Robertson 1984, Lynch and Edginton 1986, Eggers et al. 1991), coded-wire tags (Clark et al. 1985, Shaul et al. 1986), scale patterns analysis, (Wright 1965, Krasnowski and Bethe 1978, McGregor and Marshall 1982, Marshall et al. 1987), and genetic characteristics (Seeb et al. 1986, Seeb et al. 1995). The many thousands of hours, and millions of dollars spent on stock identification in North American salmon fisheries attests to the importance attached to stock composition information by scientists concerned with management.

The best example of how stock identification functions with appropriate monitoring to provide the information necessary to manage sustainable yields from salmon populations is found in the current management of the sockeye salmon fishery in Bristol Bay, Alaska (Fried and Yuen 1987). When accompanied with adult spawning escapement enumeration, stock identification of the catches makes it possible to annually determine the status of individual salmon stocks. Knowing the annual status of each stock makes it possible to formulate fishing regulations which protect the diversity and productivity of each stock. For example, as annual landings records attest, the sockeye salmon of Bristol Bay, Alaska, have been intensively commercially harvested since the third quarter of the 19th century (Mundy, in press). Under virtually unrestricted fishing from 1884 to 1927, annual Bristol Bay sockeye catches rose rapidly to average 15 million adults per year . Annual catches fluctuated greatly, occasionally exceeding 20 million, but otherwise steadily declining under a limited federal management regime, until the fishery was put under a management-by-escapement-objective program in 1954. Under the new regime, stock identification was accomplished by limiting the harvesters to "terminal areas" in the marine waters near the mouths of the major rivers where returning spawners were thought to have separated. Nonetheless, the declines in catches of Bristol Bay sockeye in the terminal areas continued down to a level of only 2.3 million in 1973 in the face of indiscriminate and uncontrolled harvests of the sockeye on the high seas by Japanese fishing vessels (Fried and Yuen 1987). After the Japanese government agreed to cease catching returning adult salmon in 1974, annual sockeye catches rose steadily to routinely exceed 20 million during the 1980's, with a catch in excess of 40 million sockeye being recorded in 1995. Since 1985, the five year moving <u>average</u> of annual catches of Bristol Bay sockeye has exceeded the <u>largest</u> single annual catch recorded prior to 1927 during the era of uncontrolled fishing . Bristol Bay is the largest of a substantial number of salmon fisheries which are successfully sustainably managed using stock identification information. For example, the management of sockeye salmon under the Fraser River Panel of the Pacific Salmon Commission (Roos 1991) is exemplary.

CONCLUSIONS FOR HARVEST AND HARVEST MANAGEMENT

1. Directed (intentional) and incidental (unintentional) harvest of CRB salmon has occurred in the absence of knowledge of harvest impacts on the abundances and viabilities of the majority of the individual native spawning populations. Viability means having a reasonable probability of survival within an arbitrary time horizon. (1)

2. Harvest rates on native spawning populations of CRB salmon from incidental and direct sources have increased since development of the Columbia River basin by western civilization in the early nineteenth century. (3)

3. Both directed and incidental harvests exert levels of mortality on salmon spawning populations which are large enough to influence their annual abundances and viabilities. (2)

4. Harvest, both incidental and intentional, has contributed to the decline in abundance of CRB salmon and it is a factor limiting their recovery but harvest restrictions in absence of habitat restoration is not sufficient. (2)

5. Interactions between mortality associated with habitat degradation (incidental harvest) and directed harvests by fisheries have lead to the extirpation of many CRB salmon populations. (3)

6. All Columbia River stocks, with the possible exception of Hanford fall chinook, are at such low levels that harvest in the ocean will have to be very low or non-existent to allow the habitat restoration proposed herein to have a reasonable chance to succeed.

GENERAL CONCLUSIONS FOR HARVEST AND HARVEST MANAGEMENT

1. Harvest regulation is a sufficient means of protecting and increasing salmon production only in the presence of reasonably pristine habitat.

2. Harvest management has failed to consider the relation of salmon abundance to other components of the ecosystem which are connected by the life cycle of the salmon.

RECOMMENDATIONS FOR HARVEST AND HARVEST MANAGEMENT

1. Harvest management needs to recognize the relation of salmon abundance to other components of the ecosystem which are connected by the life cycle of the salmon.

2. Sustained yield management of a salmon population, or *deme (see NRC 1995)*, needs to be based on numerical spawning escapement goals which represent both the productive capacities of the habitats for the salmon population and all related salmon populations, geographic gradients in fishing mortality appropriate to the nature of the stock composition information for each fishery, and a zero-sum mortality allocation across all fisheries.

C. HATCHERIES AND EFFECTS OF FISH CULTURE ON NATIVE SALMONIDS

Artificial propagation is an important tool used by salmon managers in the Columbia River for the past 120 years. It was the first management activity undertaken in the basin and it has consumed a major portion of the fisheries budget over the intervening years (General Accounting Office, 1992). In the early years of its development, artificial propagation of salmon was carried out at a small scale in low cost facilities and required little effort. However by as early as 1898, 26 million salmon fry were being released from hatcheries into the Columbia Basin each year. These early attempts at large scale propagation were largely ineffective (Columbia Basin Fish and Wildlife Authority, 1990), thus early hatcheries may not have had a significant effect on the number of adult salmon returning to the river. Nevertheless, the program did have a lasting and major influence on fisheries management philosophy and approach. Consequently, understanding the growth and evolution of the hatchery program is an important starting point for anyone attempting to understand the current status of salmon in the Columbia River basin.

Hatcheries are still a major part of the restoration program and they make a significant contribution to the remnant runs of salmon into the river. Today, about 80 percent of the adult salmon and steelhead entering the Columbia River were hatched and reared in a hatchery (Northwest Power Planning Council, 1992). Between 1981 and 1991, hatcheries consumed 40 percent of the $1.3 billion spent on salmon restoration in the basin. Furthermore, about 50 percent of the increase in salmon production predicted to result from the Council's program is expected to come from artificially propagated fish (Northwest Power Planning Council, 1994, RASP 1992) and much of this through supplementation projects. Hatcheries have had a strong influence on the past attempts to rehabilitate depleted salmon stocks in the Columbia Basin, and the salmon management institutions continue to expect major contributions from hatcheries in the future. However, the National Fish Hatchery Review Panel (Putz and Chairs), 1994), solicited by the U.S. Fish and Wildlife Service to provide outside objective evaluation of the federal fish hatchery program) and the National Research Council (NRC) have recently called for significant changes in the approach, operation and expectations from artificial propagation (Putz and Chairs), 1994; National Research Council, 1995). The Putz et al. report (1994) provides detailed recommendations that would integrate the federal hatchery system into a support role for ecosystem management, including restoration of ESA stocks.

Whether the region's management institutions are willing or able to act on those recommendations is a major uncertainty. Because of the dominant role hatcheries have, and may still play, the review of science in the current fish and wildlife program requires an understanding of the positive and negative contribution of artificial propagation to the status of Pacific salmon in the basin. The purpose of this report is to provide a part of that understanding.

In the section below, we first describe the history and development of the hatchery program and second describe the impacts of hatcheries on salmon in the Columbia Basin. It is generally recognized that the early hatcheries made little or no contribution to salmon production in the basin, so prior to 1930, we emphasize the way hatcheries influenced management policy. After 1930, with the help of a strong emphasis on science, hatcheries slowly improved and began making significant contributions to the fisheries especially after 1960. We describe hatchery evaluations carried out after 1930 and the emergence of new objectives for the use of artificially propagated fish. The final section describes the positive and negative of hatcheries on Pacific salmon in the Columbia River.

Hatcheries In The Columbia Basin Before 1930

In 1877, in response to a perceived decline of the spring run of chinook salmon, and to avoid proposed restrictions in the fishery, Livingston Stone was sent to the Columbia River to help the Oregon and Washington Fish Propagating Company (OWFPC) build and operate a hatchery (Stone, 1879; Hayden, 1930). A site on the Clackamas River was selected and the hatchery buildings and a rack across the river were constructed. OWFPC closed the hatchery five years later in 1882. In 1888, it was reopened and taken over by the state of Oregon (Cobb, 1930). After 1888, there would never be another year in which the reproduction of salmon in the Columbia Basin was entirely natural. By 1928, 15 hatcheries were operating in the basin and a total of 2 billion artificially propagated fry and fingerlings had been released into the river (Figure 8.3).

Because chinook salmon, especially the spring and summer races, made the highest quality canned product and brought the highest prices, fishermen targeted that species in the early fishery (Craig and Hacker, 1940). The early hatchery program also focused exclusively on the chinook salmon (Figure 8.4); however, when the abundance and harvest of chinook salmon began to decline, the fishery switched to other species and the hatcheries followed. Coho salmon and steelhead were propagated in hatcheries beginning about 1900; chum and sockeye salmon were taken into the hatchery program about a decade later (Cobb 1930).

Objectives - The objectives of early fish culture efforts were entirely utilitarian: i.e., to gain control over the production of salmon (Goode, 1884) and maintain a supply of fish for the salmon industry in the face of intensive harvest (e.g., OSBFC 1887, (Commissioners, 1888)). The salmon industry supported hatcheries as an alternative to other forms of conservation such as a restriction in the harvest (DeLoach, 1939). Additionally, the policies governing the early hatchery program reflect overly optimistic expectations of mangers and their belief that artificial propagation was more efficient than natural production.

Assumptions - Salmon managers believed natural reproduction was inherently inefficient and wasteful. It was subject to major, uncontrolled sources of mortality, which could be reduced or eliminated through artificial spawning and incubation in a protected environment (Foerster, 1936; Hedgepeth, 1941). These assumptions are reflected in the hatchery policy of the U. S. Fish Commission, which was to make:

> *". . . fish so abundant that they can be caught without restriction, and serve as cheap food for the people at large, rather than to expend a much larger amount in preventing the people from catching the few that still remain after generations of improvidence."* (Goode 1884, p. 1157)

The belief that protection of incubating eggs in hatcheries would make salmon so abundant that regulations would be unnecessary suggests that carrying capacity or density dependent limits to production were not considered. However, by 1894, after 22 years experience with artificial propagation and few tangible results, the U. S. Fish Commission reduced its expectations for artificial propagation. Marshall McDonald, who succeeded Spencer Baird stated,

> *". . . we have relied too exclusively upon artificial propagation as a sole and adequate means for maintenance of our fisheries. The artificial impregnation and hatching of fish ova and the planting of fry have been conducted on a stupendous scale. We have been disposed to measure results by quantity rather than quality, to estimate our triumphs by volume rather than potentiality. We have paid too little attention to the necessary conditions to be fulfilled in order to give the largest return for a given expenditure of effort and money."* (McDonald, 1894, p. 15).

McDonald raised several questions regarding the use of hatcheries including three important points that are still valid today:

1) a warning regarding an over dependence on hatchery production as a substitute for stewardship;
2) a criticism of evaluations based on the quantity of juveniles released rather than the quality of the adult populations; and
3) a recommendation for the need to evaluate the quality of the receiving waters in watersheds to be stocked with hatchery fish.

However, McDonald's reservations did not diminish the enthusiasm for artificial propagation.

The first hatcheries in the Columbia Basin were built less than 20 years after Darwin (1859) published his evolutionary theories. Concepts such as reproductive isolation, natural

selection and local adaptation had not yet become a part of science. Salmon from different rivers were believed to be genetically similar (Ricker, 1972) and interchangeable, consequently mass transfers of fish among streams were common. For example, when Bonneville Hatchery was constructed in 1909, one of its chief purposes was to serve as a central clearing house for the distribution of salmon eggs throughout the region (Figure 8.5). Eggs were brought into Bonneville Hatchery from distant rivers and hatcheries, held to the eyed-stage, then either the fry were released from Bonneville Hatchery into the Columbia River or the eyed eggs were shipped to hatcheries on other rivers. The source stream and the ultimate destination of a group of eggs was rarely the same.

Evaluations - During their first 80 years that hatcheries were operated in the Columbia River, scientifically-based evaluations did not exist. Claims of success for the hatchery program were based on short-term correlations; evidence that was weak at best, or on no evidence at all. The early history of the hatchery program is marked by extravagant and undocumented claims of hatchery effectiveness. For example, in 1883, George Brown Goode of the U.S. Fish Commission told the International Fisheries Exhibition in London, England that the Pacific salmon fisheries in the Sacramento and Columbia rivers were under the complete control of fish culture (Maitland, 1884). When Goode made that claim, the only hatchery on the Columbia River had been closed for two years (Cobb 1930).

Early experiments, based on returns of fin-clipped hatchery fish, were poorly designed and executed and did little more than confirm that some of the fish reared at hatcheries returned as adults (Game, 1904). Declining or fluctuating catches in spite of an increasing number of fry released from hatcheries (Figure 8.3), discouraged fishery managers (Oregon Department of Fisheries 1908) and led in 1911, to an experimental change in the hatchery program. The common practice at the time was to release the salmon shortly after hatching and before they started to feed. In the experiment, hatcheries reared small lots of juvenile salmon for several months and released them at larger sizes. The catch increased in 1914, the year managers expected the first returns from their experiment. After five successive years of improved catches in the Columbia River, the Oregon Fish and Game Commission announced the success of their experiments:

> *"...this new method has now passed the experimental stage, and ...the Columbia River as a salmon producer has 'come back.' By following the present system, and adding to the capacity of our hatcheries, thereby increasing the output of young fish, there is no reason to doubt but that the annual pack can in time be built up to greater numbers than ever before known in the history of the industry..."* (Comm., 1919).

At the same time, the State of Washington claimed that the increase in harvest in 1914 was due to an increase in production from their hatcheries (WDFG 1917). Subsequent review

indicated that the claims of hatchery success were premature and the increased catch was not caused by the new methodology (Johnson, 1984) and probably had little to do with artificial propagation in Oregon or Washington. Instead, the increase in harvest from 1914 to 1920 was consistent with the pattern of variation in harvest for the previous 20 years (Figure 8.6) and probably resulted from favorable environmental conditions. For example, the 1914 chinook salmon run into the Umatilla River, which had no hatchery, also increased dramatically (Van Cleve and Ting, 1960), supporting the suggestion that the increase in harvest was a response to natural climatic fluctuations.

In 1914, Willis Rich initiated studies of the life history of chinook salmon which had two practical purposes: 1) to determine the value of hatchery work; and 2) to understand the differences in early life history between spring and fall chinook (Rich, 1920). The latter was important because the spring chinook were more valuable commercially and their increase through artificial propagation was an important objective of the industry. Rich (1920) initiated several marking experiments at hatcheries in the basin to test the efficiency of hatchery practices and to test the homing ability of chinook salmon. He also examined scale patterns from collections of juvenile wild salmon captured throughout the lower Columbia River. The marking experiments also allowed him to verify his interpretation of scale patterns on unmarked salmon (Rich and Holmes, 1929). Rich's marking experiments were a major improvement over earlier "evaluations", but they did not come close to the standards of experimental design used in later evaluations, e.g. (Wahle et al., 1974; 1978). At the time of Rich's experiments, the institutional infrastructure needed to coordinate coastwide recovery of marked salmon did not exist.

Based on his observations on the timing of the migration of juvenile chinook salmon, Rich (1920) concluded that the release of sack fry should be terminated. He recommended that fry be held in the hatchery and released during the natural migration. He also recommended that juveniles be allowed to migrate out of the hatchery ponds on their own volition. One of the more important contributions from Rich’s studies was the acquisition of data, which later contributed to his synthesis paper on the importance of stocks or local breeding groups to the maintenance of productive salmon fisheries (Rich, 1939).

None of the early studies attempted to evaluate the relative contribution of artificially and naturally propagated salmon; i.e., to answer the question: Are hatcheries making a significant contribution to the adult returns to the river?

Nationally, by the 1920s, biologists were beginning to question the efficacy of fish culture during its first 50 years and as a result hatchery programs came under increasing criticism (Wood, 1953). The first scientific evaluations of hatchery programs reinforced the growing skepticism. Studies involving yellow-pike perch in lakes Huron and Michigan (Hile, 1936), whitefish in Lake Erie (Van Oosten, 1942), and Atlantic salmon in the Penobscot River, Maine from 1872 to 1939

(Rounsefell, 1947) concluded that artificial propagation was not significantly more efficient than natural production and in the case of the Atlantic Salmon, that hatcheries were not able to prevent a decline in abundance. The lack of rigorous, scientific evaluation of the hatchery programs for Pacific salmon led Cobb (1930) to conclude that artificial propagation was a threat to the continued existence of the Pacific salmon fishery. Cobb was not opposed to artificial propagation, but he believed that managers had to put aside their optimism and stop relying on hatcheries alone to increase or maintain the fishery.

Results - With all the clarity of hindsight, it is now generally recognized that the early hatchery programs had little positive impact on the abundance of salmon in the Columbia River (Columbia Basin Fish and Wildlife Authority, 1990). Nevertheless, it is impossible to estimate the impacts of massive stock transfers, stream racking, and the overall mining of eggs from productive, wild populations of salmon, although they may have been considerable.

Perhaps the greatest impact of the early hatchery program was its influence on fisheries management philosophy and direction. As suggested in the U. S. Fish Commission's hatchery policy, fish culture was viewed as an alternative to other forms of management, such as harvest regulation or habitat conservation. In addition, hatcheries were also viewed as a means of compensating for production lost through habitat degradation (Lichatowich and Nicholas, In press). If hatcheries could compensate for lost and degraded habitat, managers could afford to give habitat protection and restoration a lower priority, which they did. By 1932, 50 percent of the best spawning and rearing habitat in the Columbia Basin had been lost or severely degraded (Oregon Fish Commission, 1933). This loss and the loss of habitat that continued after 1930 is in part, the legacy of over optimism regarding the effectiveness of artificial propagation.

That this philosophy has continued to the present is clearly shown in the distribution of expenditures for salmon protection in the Columbia River prior to 1980. Less the 1 percent of the funds were spent on habitat, whereas 43 percent of the expenditures went to the hatchery program (General Accounting Office, 1992). In recent years, the situation has improved, but expenditures on habitat are still only 6 percent of the total; hatchery expenditures are 40 percent of total (Office, 1993).

Artificial propagation not only influenced attitudes towards habitat protection, but the overly optimistic expectations and a tradition of inadequate evaluation has extended to the present. After 120 years in which hatcheries have been a primary management tool in the basin, there has never been a comprehensive evaluation of the program.

Hatcheries In The Columbia Basin After 1930

Declining harvests and the failure of the hatchery programs to prevent depletion eventually convinced salmon managers that artificial propagation needed a scientific approach. However, such an approach required the assistance of biologists, basic research, and stream survey information. But in the early decades of this century, state fish commissions, which had been dominated by fish culturists, often did not trust or hire biologists (Moore, 1925). The growing criticism of the hatchery programs and the call for the development of a scientific approach to propagation, e.g., (Culler, 1932; Huntsman, 1937; Needham, 1939) eventually led the Fish Culture Division of the American Fisheries Society (AFS), to question the ability of hatcheries to perform the tasks that had been assigned to them (Gottschalk, 1942). It was becoming clear that artificial propagation had to be based on science, rather than blind optimism.

Objectives - Nevertheless, the objectives of the hatchery program after 1930 remained utilitarian: i.e., to augment declining natural production of salmon and steelhead and maintain a supply of salmon for the fishing industry in the face of intensive harvest. Managers remained overly optimistic about their expectations and predictions for the success of hatcheries and those in the U. S. did little to rigorously evaluate the efficacy of hatcheries themselves or of the overall hatchery program.

Assumptions - Scientific management emphasized the principle of supply and demand, which is best exemplified in the catchable trout program (Bottom, In Press). Catchable sized trout are delivered to the stream in the right quantity to meet the demand. The catchable trout program counted on little or no long-term survival of the planted fish. Therefore, the stream, its habitat, carrying capacity and food gradients were not important considerations (Wood, 1953). The shift to smolt releases in anadromous salmonids can be considered the equivalent to the catchable trout program. As hatchery programs shifted to smolt releases, it diminished the importance of the stream as an integrated ecosystem. The rivers became merely channels to transport smolts to sea (Ortmann et al., 1976).

Salmon managers generally remained convinced that artificial propagation could compensate for the basinwide destruction of habitat in the Columbia River watershed (Schwiebert, 1977). Managers predicted that genetic selection in the hatchery program would produce strains of steelhead suited to the changing environment of the Columbia River (Ayerst, 1977). Through a combination of hatcheries and other technology such as transportation and spillway deflectors salmon and steelhead populations would be restored in a few years and ultimately; in the Snake River, would return in numbers greater than existed before (Ebel, 1977).

Eighteen years later, chinook and sockeye salmon from the Snake River are on the Endangered Species List. Several environmental groups are considering petitions to list Snake River steelhead; because their numbers appear to be declining and following the same downward trajectory as the Snake River chinook races. The National Fish Hatchery Review Panel and the National Research Council (NRC) concluded a major revision in the role and objectives of artificial propagation is necessary (Putz and Chairs), 1994; National Research Council, 1996). In general, the reviews recommended that hatchery programs become integrated into comprehensive ecosystem restoration plans and work toward conservation objectives, rather than focusing on the production of fish for harvest (Flagg et al., 1995).

Evaluation - In 1922, the British Columbia Fisheries Commission was concerned about the lack of any positive results from its hatchery program for sockeye salmon, so it recommended an evaluation be carried out. The Commission stipulated that the study be carried out under competent scientific supervision and R. E. Forester was assigned the task. The question to be addressed by the study was also a departure from the norm. The study was designed to not only evaluate the number of juveniles released from the hatchery and the number of adults returned; it would evaluate the benefits of artificial propagation by comparing the difference in contribution from natural and artificial propagation in a controlled system where both could be monitored (Foerster, 1936). The study was carried out at the Cultus Lake sockeye salmon hatchery in the Fraser River.

The study monitored the contribution of natural and artificial propagation for 10 years. No significant difference in the efficiency of natural and artificial propagation was found. Because the hatchery could incubate only a small fraction of the eggs in the spawning population, the small incremental increase in adult returns produced by artificial propagation was not worth the expense of the hatchery. Based on this study, British Columbia closed all its sockeye salmon hatcheries (Foerster 1936). Foerster not only conducted one of the earliest scientific evaluations of a hatchery program for Pacific salmon, but he tested the fundamental assumption underlying all salmon hatcheries (artificial propagation was more efficient than natural reproduction) and found it to be false at least as far as sockeye salmon was concerned. However, Foerster's study only evaluated the difference in survival between natural and artificial propagation of sockeye salmon when the hatchery fish were planted into Cultus Lake or its tributaries as fry or eyed eggs (Foerster 1936).

In 1934, shortly before Foerster completed his study, Salo and Bayliff (1958) started an evaluation of natural and artificial propagation in Minter Creek, a small stream in Puget Sound. They compared the relative survival and contribution of wild and artificially propagated coho salmon which were reared for extended periods before release, rather than the fry that Foerster

used in the Cultus Lake study. At the time Salo and Bayliff's study was initiated, most hatcheries released fry with little or no feeding, conditions that were similar to those evaluated in Foerster's study. However, hatcheries were gradually shifting from fry releases to extended rearing on the assumption that larger, older fish would survive better after release from the hatchery. Like Foerster's study, the Minter Creek evaluation was carried out for several years. The findings, however, differed from Foerster's.

Salo and Bayliff (1958) reported that coho salmon reared in the hatchery for extended periods of 6 to 12 months produced greater adult returns than coho juveniles from an equivalent number of wild spawners. The Minter Creek study showed that under the right hatchery practices, artificial propagation could be more efficient than natural production and artificially propagated salmon could significantly increase adult production in small populations. However, in the 1940s and 1950s, extended rearing presented hatchery managers with a new set of problems for which they had no clear solutions. Extended rearing required improved disease prevention and treatment and the development of nutritious feeds.

By the 1940s, individual hatcheries were fin-clipping juvenile salmon in order to evaluate returns to the hatchery from routine production or to evaluate experimental hatchery practices. Often the experiments had too few recoveries to be conclusive. The results of many of those studies are summarized by Wallis (1964).

Extended rearing in the hatcheries prompted research into the nutritional requirements of juvenile salmon and the prevention and treatment of diseases. By the mid-1960s, the development of new feeds, better prevention and treatment of diseases, and improved hatchery practices such as the optimal size and time of release started to produce tangible results (Lichatowich and Nicholas, In press). Artificially propagated salmon began making significant contributions to the fishery, however, that success created another set of ecological, genetic and management problems which are discussed later in this report.

Beginning in the 1960s, the National Marine Fisheries Service (NMFS) conducted a series of large scale evaluations of the contribution of chinook and coho salmon from Columbia River hatcheries to various fisheries in the Northeast Pacific. The 1961 through 1964 broods of juvenile fall chinook from 13 hatcheries in the Columbia Basin were given special marks (fin clips) before release so their contribution to the sport and commercial fisheries could be estimated. The evaluation was stimulated by a moratorium on new hatchery production until it could be demonstrated that such construction was economically justified (Whale and Vreeland 1978). Results of the evaluation were positive. The benefit cost ratio for all hatcheries combined for each of the brood years was 1961, 3.7:1; 1962, 2.0:1; 1963 7.2:1; and 1964, 3.8:1. The potential catch per 1,000 fish released was 1961, 6.7; 1962, 3.1; 1963, 10.0; and 1964, 6.5. Average survival for all hatcheries combined was 0.7 percent. Overall, an estimated 14 percent of the fall

chinook salmon caught in the sport and commercial fisheries from southeast Alaska to northern California originated from the Columbia River hatcheries (Wahle and Vreeland, 1978).

The NMFS repeated the fall chinook evaluation with the 1978 to the 1982 broods. Total survival for all four brood years and all facilities was 0.33 percent or about half the survival of the earlier study, however the benefit-cost ratio was still positive at 5.7:1. The overall contribution to the fishery was 1.9 adults for each 1,000 juveniles released (Vreeland 1989). The NMFS used a similar approach to evaluate the contribution made to the west coast fisheries by the 1965 and 1966 broods of coho salmon. Juvenile coho salmon from 20 hatcheries in the Columbia Basin were marked for the study. Recoveries were monitored from British Columbia to California. Coho salmon from Columbia River Hatcheries made up about 16 percent of the total catch in the sampling area. The catch from both brood years combined was 55 adults for each 1,000 smolts released for a benefit cost ratio of 7.0:1 (Wahle et al., 1974).

Results - A complete evaluation of a hatchery or group of salmon hatcheries should address three questions:

1) Do the salmon and steelhead of hatchery origin contribute to the fisheries and/or escapement and is the economic value of that contribution greater than the cost to produce it?
2) Is the level of contribution consistent with its purpose or objective of the hatchery? For example, if a hatchery is intended to replace natural production lost due to habitat degradation, this question asks did the hatchery, in fact, replace the lost production?
3) Do artificially propagated fish add to existing natural production or do they replace it, i.e., Does the hatchery operation generate a cost to natural production through mixed stock fisheries, domestication and genetic introgression?

The NMFS evaluations were well designed and executed, but they only addressed the first question. That was a serious omission. From a historical perspective, it is clear that artificial propagation has failed to replace natural production lost due to habitat degradation. In addition, hatcheries have caused direct and indirect costs to the existing natural production, e.g., (Flagg et al., 1995; Utter et al., 1995).

Coho smolts released from Columbia River hatcheries achieved high levels of survival in the late 1960s and early 1970s, and although some biologists recognized that favorable ocean conditions contributed to improved production, managers largely credited hatcheries for the improved harvests which "...while most encouraging, was not unplanned nor unexpected" (Oregon Fish Commission 1964).

Columbia River coho salmon are a major contributor to the Oregon Production Index (OPI), which is a measure of the abundance of coho salmon south of Illwaco, Washington

(Oregon Deptartment of Fish and Wildlife 1982). The hatchery and wild stocks of coho salmon from the Columbia River are managed as part of the (OPI). The history of ocean harvest of coho salmon in the OPI illustrates the need for more comprehensive evaluations of hatchery programs. It's now understood that the pattern of production with lows from the 1930s to the 1950s, followed by a period of high production in the 1960s and 1970s and another trough in the 1980s and 1990s (Figure 8.7), reflects the response to changing ocean conditions and climate patterns, rather than only to the release of hatchery reared coho (Nickelson 1986; Lichatowich in press).

Prior to 1960, most of the coho salmon harvested in the OPI were naturally produced (Oregon Deptartment of Fish and Wildlife 1982). After 1960, artificially propagated salmon made up an increasing proportion of the catch. Unfortunately, the contribution of hatchery and wild coho salmon to the OPI ocean harvest was monitored in only eleven of the years between 1960 and 1992 (Figure 8.8). What appears to be a recovery in the 1960s and 1970s (Figure 8.8) was dominated by artificially propagated coho salmon. Wild fish showed little sign of recovery. Harvest targeted on the dominant hatchery component of the OPI had significant impact on the natural production of Oregon's coastal and lower Columbia River coho stocks. The mixed stock (hatchery - wild) fishery in the OPI has consistently over-harvested the wild coastal stocks of coho salmon. Of 55 coastal stocks of coho identified by ODFW, 41 were classified as depressed (Nickelson et al. 1992) and between 1981 and 1991, escapement goals were met in only 3 of the 11 years (Pacific Fishery Management Council 1992).

Wild coho salmon from the lower Columbia River, which were also part of the OPI, are largely extinct, although remnant populations may still exist in the Clackamas, Hood, and Klickitat rivers. High harvest rates on the mixed hatchery and wild stocks, which often exceeded 90 percent, were exacerbated by hatchery practices. Flagg et al. (1995) identified the following hatchery practices that contributed to the decline and extirpation of coho salmon in the lower Columbia River:

1) Selection for early spawners,
2) Fry stocking that exceeded carrying capacity, and
3) Planting fry that were larger than their wild counterparts.
4) Inter-hatchery stock transfers.

Influence on management of Columbia River salmonids

In 1930, John Cobb, Dean of the College of Fisheries at the University of Washington, listed artificial propagation as one of the threats to the fishing industry for Pacific salmon.

> "*In some sections an almost idolatrous faith in the efficacy of artificial culture of fish for replenishing the ravages of man and animals is manifested, and nothing*

> *has done more harm than the prevalence of such an idea. While it is an exceedingly difficult thing to prove, the consensus of opinion is that artificial culture does considerable good, yet the very fact that this can not be conclusively proved ought to be a warning to all concerned not to put blind faith in it alone*." (Cobb 1930, p 493).

Artificial propagation of salmon was established in the Columbia Basin before state management institutions were created or before the U. S. Fish Commission established a permanent presence in the Pacific Northwest. In the decades after the management institutions were created, their mission was primarily to build and operate hatcheries. The way in which institutional budgets were expended confirms the priority and emphasis that was given to artificial propagation. In 1922, 76 percent of the Oregon Fish Commission's budget was expended on artificial propagation (Shoemaker and Clanton, 1923). In the Columbia River, since the development of the hydroelectric system, artificial propagation has consumed the largest share of the budget (Figure 8.9). Prior to 1980 habitat received less than one percent of the funding; after 1981 habitat received about 6 percent. These figures reflect a national trend. From 1989 to 1993, the average expenditures of Federal Aid in Sportfish Restoration Program funds in 36 states included 42 percent to hatchery-related projects while only one percent of the funds went to habitat-related projects (McGurrin et al., 1995).

Perhaps the most important legacy of the hatchery program throughout its 120 history has been its influence on management, rather than any direct contribution to the various fisheries. Belief in the success of artificial propagation, which was largely unsubstantiated prior to 1960, made compromise leading to habitat destruction and over-harvest easier to accept (Hilborn, 1992; Lichatowich and Nicholas, In press). Salmon populations throughout the northwest, similar to the one that persists in the Hanford reach, were destroyed in part by faith that hatchery technology would maintain production. Hatcheries have influenced management in two important ways: First, in the late 1800's and through to the 1970's, management institutions were willing to trade habitat for hatchery programs. The result was a massive shrinkage in the natural production base and a dependence on a large, expensive hatchery program which could only maintain salmon and steelhead at a fraction of their historical abundance. Second, management agencies are now forced to provide major emphasis and allocate resources to the restoration of those degraded habitats in an attempt to enhance the depleted base of natural production.

For the past two decades, salmon management has been changing. From a program almost entirely devoted to hatchery production and harvest regulation, management is shifting to a greater concern for natural production. In recent years, the states of Oregon and Washington have conducted extensive surveys of the status of naturally reproducing stocks of salmon and

steelhead (Wash. Dept. of Fisheries, 1993; Kostow, 1995). Hatchery programs are being designed to minimize their impact on natural production and new programs are subject to extensive monitoring (Bowles and Leitzinger, 1991; Messmer et al., 1992). Harvests are severely restricted to protect weak natural stocks and biologists are recommending that hatchery programs be revised to include conservation objectives, instead of merely supplying fish for harvest (Flagg et al.1995). Which direction an emerging new role for artificial propagation will take is hard to predict, however biologist Gary Meffe has outlined one approach that has merit:

> *"... a management strategy that has as a centerpiece artificial propagation and restocking of a species that has declined as the result of environmental degradation and over exploitation, without correcting the causes for the decline, is not facing biological reality. Salmonid management based largely on hatchery production, with no overt and large scale ecosystem-level recovery program is doomed to failure. Not only does it fail to address the real causes of salmonid decline, but it may actually exacerbate the problem and accelerate the extinction process."* (Meffe, 1992, p 351).

Biological Effects of Hatcheries

In spite of over a century of reliance on hatchery production to bolster or mitigate natural production, and unheeded cautions about the effects and efficacy of hatchery mitigation (Rich, 1939; Schuck, 1943; Reisenbichler and McIntyre, 1977; Reisenbichler and McIntyre, 1986) , only recently have fisheries managers begun to seriously investigate the effects that cultured fish can have on natural populations of salmonids (Hindar et al., 1991; Krueger and May, 1991; Washington and Koziol, 1993; Busack and Currens, 1995; Campton, 1995; Leary et al., 1995). In part, this effort is fueled by a growing recognition that local salmonid populations (or aggregates of populations; i.e., a metapopulation) are frequently distinct from other conspecific populations (or aggregates) (Allendorf and Utter, 1979; Ryman and Utter, 1987; Gharrett and Smoker, 1993). Past stocking efforts, particularly where non-indigenous stocks were used, have resulted in unanticipated detrimental effects on natural fish populations, rather than bolstering natural production as hoped (Washington and Koziol, 1993; Schramm and Mudrak, 1994; Utter et al., 1995).

Interactions between hatchery and wild fish can occur directly through interbreeding or indirectly through ecological and behavioral interactions (Waples et al., 1991) and can alter the genetic architecture of a species (and natural populations) by changing the distribution of genetic variation within and among populations (Allendorf and Leary, 1988; Allendorf, 1991; Utter et al., 1995). Genetic changes also can occur in hatchery stocks themselves, increasing the likelihood

that detrimental consequences will occur when natural stocks experience contact with hatchery stocks (Reisenbichler, 1995). Hindar et al. (1991) reviewed and summarized the genetic effects (both direct and indirect) of cultured salmonids on natural salmonid populations and concluded that where genetic effects have been documented, they always appear to be negative in comparison with the unaffected native populations The one-sidedness of the empirical observations in favor of the greater fitness of local populations resulted from a lack of observations in the opposite direction, rather than from a bias in selecting references.

Campton (1995) presented another perspective on the genetic effects of hatchery fish on wild Pacific salmon populations, in which he notes the genetic effects on wild fish can be attributed to either the direct biological effects of hatcheries and hatchery fish or the indirect -- and biologically independent -- effects of stock transfers, mixed-stock fisheries on hatchery and wild fish, and other human factors related to management. The latter set of factors relate to hatchery management philosophy and practices; whereas the direct biological effects describes the genetic effects of hatcheries and artificial propagation on hatchery fish, as well as the genetic consequences of hatchery fish interbreeding with wild fish.

Direct Genetic Effects - Direct genetic effects are those that result from hybridization of cultured fish with wild fish. The effects of such interactions are generally negative and usually result in reduced fitness in the wild population, due to the breakup of various coadapted gene complexes that are linked to local adaptation, performance, and fitness in the local population. Progeny of such matings usually suffer increased mortality and lowered reproductive success as compared to progeny of native wild fish (Leary et al., 1995). Numerous studies exist that document losses of within- or among-population genetic variability as a result of genetic interactions between hatchery and wild fish (Allendorf and Ryman, 1987; Currens et al., 1990; Hindar et al., 1991; Leary et al., 1995; Williams et al., 1996).

Within-Population Variability. Loss of within-population variation is usually linked to small effective population size (N_e), where allelic diversity can be lost through drift or sampling error. Generally, wild populations are not effected by this process, unless their numbers reach very low levels (like many of the current Idaho salmon stocks); however, considerable data exist documenting the debilitating effect of small N_e on hatchery populations.

In those few instances where hatchery and wild fish populations are similar genetically and slightly inbred, heterosis, or F_1 hybrid vigor may occur. However, as genetic differences between the hatchery and wild stocks increase (usually measured by genetic distance), the more likely it is that outbreeding depression will occur and lead to reduced fitness in the F_1 hybrids.

Recombination in the F_2, and subsequent generations, is likely to reduce fitness even further (Emlen, 1991; Waples, 1991).

Among-Population Variability. Reductions in among-population genetic variances can occur where a single broodstock is used over a wide geographic area (Reisenbichler and Phelps 1989), such as has occurred with the Carson spring chinook stock and the Skamania steelhead stock, or where substantial numbers of cultured fish have strayed into natural populations, as has occurred in Norwegian rivers due to net pen escapees (Hindar et al., 1991; Gausen, 1993; Heggberget et al., 1993). Reductions in reproductive fitness are the most likely result of genetic interactions between hatchery and wild fish (Hindar et al., 1991; Waples, 1991). Such reductions in fitness are due to outbreeding depression (Figure 8.10), where two genetically dissimilar individuals (or stocks) interbreed.

Indirect Genetic Effects - Indirect genetic effects refers to the ecological and behavioral interactions between wild and hatchery fish that occur without direct genetic exchange. However, the interactions have genetic, and therefore fitness, consequences (Waples, 1991). Any factor that causes a reduction in population size can have an indirect effect on the genetic structure of wild fish populations, as well as increasing the risk of local extinction of that population through stochastic environmental perturbations (Soule, 1987; Lande, 1988). Factors that can adversely effect population size include: competition; hatchery stocking densities that exceed carrying capacity; increased physiological stress associated with agonistic encounters; predation; disease; harvest of hatchery target (underharvest - increases opportunities for hatchery fish to stray or to breed with wild fish; overharvest - also harvests wild stock and reduces its population size); and altered selection regimes. There is a substantial body of literature, which is not reviewed here, that documents interactions between wild and hatchery fish for these factors, e.g., (Fausch, 1988, presents a review of competitive interactions between introduced and native fishes in stream systems). Some of these factors can have profound effects on genetic variability and population viability. An extreme example that illustrates the some of the negative consequences that can result from large scale interactions of hatchery raised fish and wild fish occurred in Norwegian Atlantic salmon populations. Heggberget et al. (Heggberget et al., 1993) note that disease transfer from farmed fish into native fish, after a catastrophic release of net pen fish, led to the complete extirpation of more than 30 native populations. Many of these factors alter the selection regimes faced by populations, which can shift the population's genetic and phenotypic attributes, as well as numerical abundance.

Directional Selection. Character values are typically distributed in normal frequency distributions (Figure 8.10.1) that are bell-shaped. Directional selection happens when selection

occurs for a character value other than the mean (Figure 8.10.2). A typical example of this type of selection is the effect that fishing pressure (and various types of nets and gear) have in selectively harvesting larger fish, causing the mean size of fish in the run to decrease.

Stabilizing Selection. Stabilizing or truncating selection happens when selection occurs specifically for the mean character, which will act to reduce overall variation, i.e., diversity (Figure 8.10.3). Management actions that focus on mean values may promote selection of this type. An example of this would be the reduction observed by fish passage personnel at John Day Dam over the last 10-15 years in the number of wild smolt emigrants during the September 1 - November 30 time period. These observations suggest that smolts that emigrate in mid-April to mid-June are favored by some set of circumstances related to human development, while those outmigrating in the early spring or the fall months appear to have been eliminated.

Genetic Changes to Hatchery Stocks - Genetic changes, and the potential for such changes, have been well documented for hatchery stocks. Reductions in overall levels of genetic variability, usually due to small effective breeding population size associated with hatchery practices, and concomitant reduced fitness attributed to inbreeding depression have been reported in some hatchery stocks (Allendorf and Phelps, 1980; Leary et al., 1985; Allendorf and Ryman, 1987; Waples and Smouse, 1990), but not all hatchery stocks (Utter et al., 1989). Genetic changes in hatchery stocks can also be attributed to artificial selection or domestication selection.

Artificial Selection. Artificial selection is directed or inadvertent selection that can occur in the hatchery environment (Waples 1991; Reisenbichler 1995). A well-known example of this is the common advancement of time of spawning in hatchery strains rainbow trout and timing of spawning migrations of Pacific salmon and steelhead trout that occurs from a greater than representative contribution to spawning populations from early maturing fish.

Domestication Selection. Domestication selection is natural selection occurring within the hatchery environment, whereby fish that perform better in the hatchery environment have a selective advantage (Reisenbichler and McIntyre 1977). In general, domestication selection results in increased fitness in the hatchery environment, but decreased fitness under wild conditions (Campton 1995).

Genetic Changes to Wild Stocks - Numerous studies have documented direct genetic interactions between wild and hatchery fish (Campton and Johnston, 1985; Campton and Utter, 1985; Bartley et al., 1990; Currens et al., 1990; Forbes and Allendorf, 1991; Eriksson and Eriksson, 1993; Leary et al., 1995; Utter et al., 1995; Williams et al., 1996). Despite a large body of evidence documenting genetic interactions between hatchery and wild salmonids, and correlative observations of declines in abundance of natural salmonids, little empirical evidence

exists documenting reductions in fitness in wild populations as a result of genetic interactions with hatchery reared fish, but see Gharrett and Smoker (1991) (1991) and Philipp and Clausen (1995). Data on fitness have proven notoriously difficult to collect, nevertheless, there is a substantial body of established theory that is supported widely by emperical observation from other vertebrate species and supported to some extent by observation on salmonids indicating that interbreeding between strains of hatchery fish and wild fish can result in offspring with reduced fitness.

.

Recent Uses of Hatcheries

Mitigation for Hydropower Development

Grand Coulee Fish Maintenance Project - The first major program designed to compensate for hydroelectric development in the Columbia basin was the Grand Coulee Fish Maintenance Project. With a height of 500 ft, Grand Coulee Dam was too high to successfully pass salmon via a ladder or elevator. Salmon managers considered the construction of a hatchery immediately below the dam, but engineering problems caused the biologists to look for an alternative. The plan eventually implemented had three key elements: 1) adult salmon and steelhead were trapped in the ladders of Rock Island Dam from 1939 to 1943 and the fish taken to holding areas; 2) some adults were released into rivers selected for the transplanted runs and allowed to spawn naturally; and 3) the remaining fish were held for artificial propagation at Leavenworth hatchery. The streams which received the transplanted fish were Wenatchee, Entiat, Methow and Okanogan rivers and Lake Osoyoos (Fish and Hanavan, 1948) .

The results of the fish maintenance program were evaluated by comparing the contribution of relocated stocks to the Columbia River escapement above Bonneville Dam before the Grand Coulee cut off salmon migration (1938-1942). Counts at Rock Island Dam were used as estimates of the escapement of relocated stocks. Based on this analysis, Fish and Hanavan (1948) regarded the Grand Coulee Salmon Salvage Program a success. However, twenty four years later Ricker (Ricker 1972) gave a more pessimistic appraisal of the program and concluded that it salvaged nothing. Mullan et al. (Mullan et al., 1992) concluded that the fish maintenance program conserved the genetic diversity of the salmon stocks in the area, however, the large-scale capture, mixing and relocation of chinook salmon stocks above Rock Island Dam permanently altered the population structure and was the genesis of the present stock structure of salmon in the mid-Columbia (Utter et al. 1995).

Lower Columbia River Fishery Development Program - The current restoration program for Columbia River salmon and steelhead has its roots in the Lower Columbia River Fishery Development Program (LCRFDP), which was strongly influenced by the concepts and design of

the Grand Coulee Fish Maintenance Project. Originally, LCRFDP had an implementation life of 10 years, however, the program, with some modifications has continued to the present. As the title suggests, the program's initial objective was to concentrate salmon production in the lower Columbia River below McNary Dam. At the time it was believed that the construction of McNary Dam and the other proposed dams in the upper Columbia and Snake rivers would eventually eliminate salmon in the upper basin. In 1956, congress changed the purpose of the LCRFDP by adding fishery restoration above McNary Dam and the word "Lower" was dropped from the program title (Delarm et al., 1989) .

The LCRFDP had six principal parts:

1) Remove migratory obstructions in the tributaries to the lower Columbia River. This part of the program included the stream clearance work that removed large woody debris and reduced habitat quality in some streams;
2) Clean up pollution in major tributaries like the Willamette River;
3) Screen water diversions to prevent the loss of juveniles in irrigation ditches, and construct fishways over impassable barriers in the tributaries of the lower Columbia River;
4) Transplant salmon stocks from above McNary Dam to the lower river;
5) Expand the hatchery program by rebuilding existing hatcheries or new facilities; and
6) Create salmon refuges by setting aside the lower river tributaries exclusively for the maintenance of salmon and steelhead runs (Laythe, 1948) .

Stream clearance was consistent with management understandings and attitudes at the time, e.g., (Fisheries 1953, p. 17), but it is no longer practiced unless the obstruction presents a complete unnatural block to migration. The transfer of stocks to the lower river ignored the stock concept and the adaptive relationship between the stock and its habitat. The hatchery program was one of six parts of the program, but within a few years it was the dominant part. By 1951, hatcheries consumed 49 percent and habitat work 5 percent of the budget (unpublished budget information obtained from the National Archives PNW Center, record group 22).

Mid-Columbia Mitigation - Mitigation programs in the mid-Columbia evolved in three phases. The first phase was the Grand Coulee Fish Maintenance Project described above. From 1961 to 1967, four hatcheries and a satellite facility were constructed to mitigate for mainstem habitat inundated by five PUD projects. This second phase, originally consisted of three spawning channels (Priest Rapids, Turtle Rock and Wells) and two conventional hatcheries (Rocky Reach and Chelan). The spawning channels were later converted to conventional hatcheries. The third phase has been implemented since 1989 and is composed of the Methow hatchery and two satellite ponds, the Eastbank Hatchery with five satellites, and Cassimer Bar Hatchery. This phase

is intended to mitigate for juveniles produced in the tributaries which are lost in passage past Wells and Rock Island Dams. Monitoring and evaluation of the mid-Columbia mitigation is underway.

Lower Snake Compensation Plan - The Lower Snake River Compensation Plan (LSRCP) was developed to mitigate for the loss of fish and wildlife resources resulting from the construction of Ice Harbor, Lower Monumental, Little Goose and Lower Granite dams. The dams were completed between 1961 and 1969 (Lavier, 1976) . Planning for the compensation program started in 1966 and was approved by the U. S. Congress in 1976. The McCall Hatchery was the first facility constructed (completed in 1979), followed over the next eight years by several other hatcheries and satellite facilities. Presently, there are twelve hatcheries and eleven satellites employed in the LSRCP (Mighetto and Ebel, 1994).

Steelhead have increased in abundance as a result of the releases from LSRCP hatcheries and the program is considered successful in terms of their original objectives of the LSRCP (Mighetto and Ebel 1994), although, in 1994 the summer steelhead run was the lowest since 1982 (Wildlife 1995). Chinook salmon returns have been well below target levels. The LSRCP hatcheries were originally designed as conventional hatcheries, however in some cases, conventional hatchery operations have evolved into supplementation programs, e.g., (Messmer et al. 1992). The programs and the supplementation technology are too new to determine if they will be successful (RASP 1992; Bowles 1995).

The objective of the Lower Snake River Compensation Program did not include Snake River coho salmon or Snake River sockeye salmon, which were relatively abundant at the time LSRCP was being planned. Relatively few resources were devoted to Snake River fall chinook, with only one of twelve hatcheries being devoted to this life history type. It is worth noting that coho salmon are presently extirpated from the Snake River Basin, sockeye salmon are nearly extinct, and fall chinook are listed as endangered under the Endangered Species Act.

Summary results on uses of hatcheries

After 120 years of salmon management based largely on the assumption that artificial propagation could replace natural production in the Columbia Basin and the development of a massive system of hatcheries, its instructive to note that the most productive stock in the basin is the fall chinook population that spawns naturally in the free flowing Hanford Reach of the mainstem Columbia. In the context of the entire history of the hatchery program, and the history of salmon management in the basin, the hatchery program has failed to meet its objectives. In 1994, the smallest number of salmon and steelhead entered the Columbia River since counts began in 1938, and by 1939, salmon production was already far below historical levels. Artificial

propagation of salmon did not maintain salmon production. The early optimism that predicted hatcheries would make up for overharvest and habitat degradation has given way to the reality of depletion, closed fisheries, and a fragmented ecosystem in which natural production is severely restricted. Today the dominance of hatcheries in management programs is being questioned (Hilborn and Walters 1992; Washington and Koziol 1993; NRC 1996). New roles for hatcheries and guidelines for their operation are being developed or proposed (Putz and Chairs), 1994) (White et al., 1995), however, in the past, the hatchery program has been slow to adopt change. For example, by 1939, fish culturists recognized that the stock concept in Pacific salmon meant interhatchery transfers were detrimental (OFC 1939), however, 56 years later, Flagg et al. (1995) were still recommending that hatcheries restrict that practice.

Since 1960, the total release of hatchery reared salmonids has grown from 79 million to about 200 million (Figure 8.11) -- in recent years (1987 to 1992), the range was 179 to 221 million fish. Since 1960, the number of adult salmon and steelhead entering the Columbia River has not shown an increasing trend (Figure 8.11). although those data do not include the number of salmon harvested in interception fisheries outside the basin, which can be substantial (Lestelle and Gilbertson 1993). Prior to 1960, most of the adult salmon and steelhead entering the Columbia Basin were naturally produced (Authority 1990), however, over the past three decades the proportion of hatchery reared fish in the adult population has grown to about 80% (Northwest Power Planning Council, 1992). From a cursory examination of the overall numbers, it could be argued that in recent decades the hatchery program has accomplished its objective -- hatchery production has replaced natural production lost through habitat degradation, i.e., the increasing proportion of hatchery fish might indicate successful mitigation for habitat loss. However, reality is more complicated. The hatchery program since 1960 contains some successes, in some cases hatcheries have failed to reach mitigation goals, and hatchery practices have been directly linked to depleted natural populations.

The hatchery program for coho salmon contributed to the depletion of wild coho populations in tributaries below Bonneville Dam. Flagg et al. (1995) identified factors related to the hatchery program that contributed to the decline in natural production of coho salmon in the lower Columbia River: Excessive harvest in the fisheries targeting mixed hatchery and wild stocks; selection for early spawning broodstock; fry stocking in densities greater than the carrying capacity of the receiving stream; planting hatchery fry that were larger than the naturally produced fish; and interhatchery transfers.

In the upper Salmon River, hatchery mitigation has not replaced or maintained natural production lost due to smolt mortality, especially at the lower Snake River Dams, however, it has slowed the decline of total production (Bowles, 1993). In the South Fork of the Salmon River, hatchery mitigation has increased total production (Bowles 1993).

In the upper Snake and Columbia rivers, the present geographic distributions and genetic population structures of fall-run chinook salmon reflect stock transfers and hatchery confinements carried out between 1939-1943 under the Grand Coulee Fish Maintenance Project (GCFMP). The GCFMP intercepted upstream migratory salmonids at Rock Island Dam near Wenatchee from 1939 through 1943 for relocation in tributaries downstream of Grand Coulee Dam. In this 5-year period, almost all adult spring-run and summer-fall-run chinook, regardless of original destination, were either confined to restricted areas for natural reproduction or used in hatchery operations (Utter et al. 1995). This large-scale program, of interceptions, stock transfers, and stock mixing, permanently altered the salmon populations in the Upper Columbia River and provided the foundation for their present population structures.

Warm Springs National Fish Hatchery has successfully increased production in that river without adversely affecting wild stock production (Olson et al., 1995). This program appears to be an example of the effective use of adaptive management.

These examples suggest that the results of artificial propagation in the Columbia River since 1930 and especially after 1960 have been mixed. Unfortunately, the lack of a meaningful comprehensive evaluation doses not permit a determination and detailed description of the net effects artificial propagation. Given the current state of the salmon and steelhead in the basin it would be appropriate to conclude that in its 120 year history, the net effect of hatcheries has been negative.

Future Directions for Hatcheries

Recent reviews of the efficacy of hatcheries toward fisheries management goals, and of the impact of hatchery fish and hatchery practices on wild fish populations, all appear to lead to the same general conclusion and recommendations. In the Columbia River Basin, in spite of large-scale hatchery efforts and massive outplantings of hatchery-reared fish, the hatchery program has failed to replace or mitigate for lost natural reproduction of anadromous salmonids. New directions and visions for the hatchery program are clearly needed, and several recent reviews (National Fish Hatchery Review Panel 1995; National Research Council 1995; Campton 1995; White et al. 1995) provide them, suggesting that a new role be defined for hatcheries in general, and in the Columbia River Basin in specific. The reviews are concordant in suggesting that hatcheries should have a much smaller role in salmon production and restoration than they have had in the past. Additionally, their roles and objectives (identified individually for each hatchery) need to be coordinated into an integrated recovery and management plan for each appropriately scaled management unit (watershed or subbasin). Hatcheries need to be used cautiously, as tools, that are integrated into rehabilitation or restoration strategies that focus on habitat restoration, reduction of human-induced mortality agents, and conservation of existing genetic and life history

diversity in natural populations (Allendorf and Waples, 1996). The National Fish Hatchery Review Panel (1995) and White et al. (1995) provide detailed recommendations and suggestions for changes in the hatchery system.

Clearly there is a role for hatcheries in the management and restoration of Pacific Northwest anadromous salmonids. For example, in the case of dwindling upriver stocks, hatcheries may provide temporary, but key refuges, in which various populations might be sustained while downstream causes of mortality are removed or modified (Cuenco et al., 1993; Bowles, 1995). Similarly, hatcheries may have a temporary role in rebuilding depressed populations (e.g., through supplementation activities as described in RASP 1992). It remains to be seen, however, if there is a role for large-scale production hatcheries that is compatible with conservation and long-term management of many of our imperiled stocks (Philipp et al., 1993).

Supplementation

One of the new roles for hatcheries and artificial production in the Columbia River Basin is supplementation, where carefully selected stocks of hatchery-produced fish are used to enhance or "reseed" streams where native populations have been depressed or extirpated. Ideally, supplementation is viewed as a small scale and temporary strategy to boost naturalized production in wild stocks (Steward and Bjornn, 1990; Cuenco et al., 1993; Bowles, 1995). Supplementation is important to consider because it is currently expected to be the major tool that will be used to rebuild depressed stocks in the upper Snake Basin. Supplementation has been proposed as one important means for achieving the Council's goal of doubling adult salmon returns. Thus, much hope is being placed in a concept that remains to be tested and proven each time it is applied (Cuenco et al., 1993; Lichatowich and Watson, 1993, RASP 1992).

Supplementation envisions the use of the protected hatchery environment to obtain a survival advantage through the incubation of eggs and the early rearing stages of juvenile salmon. Those juveniles are then planted back into streams to complete their rearing under natural conditions, in the hope that they will return as adults to spawn naturally, and successfully and thereby augment natural production in the stocked watershed. In the early years of artificial propagation, the speculation that high natural egg mortality occurred was used to justify supplementation with artificially propagated salmon. Today, underseeding of tributary streams and the extremely high total mortality rates for wild salmon stocks provide the rationales for this strategy (Northwest Power Planning Council, 1992).

In the late 19th century, the crude technology of artificial propagation and poor understanding of the salmon's biology limited the chance of success. Today, the technology of fish culture in the hatchery has improved, although, the information needed to integrate artificial

and natural production systems is still not well developed (Lichatowich and McIntyre, 1987; Allendorf and Waples, 1996). Unfortunately, the rearing habitats in which juvenile salmon must live after planting have been considerably degraded. Our understanding of the ecology and genetics of Pacific salmon has improved and that understanding has placed new constraints on supplementation. The definition of supplementation adopted by RASP (Regional Assessment of Supplementation Program) (1992) underscores those constraints:

> *Supplementation is the use of artificial propagation in the attempt to maintain or increase natural production while maintaining the long term fitness of the target population, and keeping the ecological and genetic impacts on nontarget populations within specified limits* (RASP 1992, P. 6).

The constraints contained in the RASP definition are new to artificial propagation, and because they are new, there is little experience that can be used to resolve uncertainties. RASP (1992) describes some supplementation uncertainties which are given a thorough review by Steward and Bjornn (1990). The Council has stipulated (7.3B of the FWP) that fishery managers will use the RASP guidelines to plan new supplementation projects. This step is critical and managers must be held accountable for adequate planning of their supplementation projects, including adequate monitoring and procedures for adaptive management. Project plans must receive peer review from fisheries scientists and geneticists.

One of the reasons why supplementation needs critical review and evaluation is the confusion over the interpretation of what constitutes supplementation. Supplementation is generally defined as the use of artificially produced fish to augment natural production without eroding long-term fitness of target and non-target natural populations (Bowles and Leitzinger, 1991; Cuenco et al., 1993; Northwest Power Planning Council, 1994; Bowles, 1995). However, outside the published definition, common usage of the term supplementation has taken on much broader meanings. Because the term supplementation has such broad meaning, there is little practical agreement on a definition. In its broadest sense, supplementation includes various fisheries management activities including: restoration; introduction; rearing augmentation; and harvest augmentation (Miller et al., 1990; Steward and Bjornn, 1990; Sterne, 1995). Differing definitions in current use confound objectives, obscure the mechanisms for accomplishing those objectives, and circumscribe criteria used for evaluating success of supplementation programs.

Confusion over what is meant by supplementation has also hampered efforts to evaluate the effectiveness of supplementation as a tool to rebuild depressed salmon populations. This is a serious shortcoming because as much as 50 percent of the increase in salmon production projected from the systems planning model is expected to result from supplementation projects (RASP 1992). Reviews of supplementation (Miller et al., 1990; Steward and Bjornn, 1990; Hilborn and Winton, 1993; Winton and Hilborn, 1994; Bowles, 1995) indicate that in those few

instances where supplementation projects were conducted in a rigorous enough manner to permit evaluation, supplementation was rarely successful in increasing natural production, and often significant risks were incured (Reisenbichler and McIntyre, 1977; Nickelson et al., 1986; Reisenbichler and McIntyre, 1986; Waples and Do, 1995; Allendorf and Waples, 1996). In contrast, success has been verified in programs that introduce fish into vacant habitat, either new areas or areas from which they had been previously extirpated (Cuenco et al., 1993), although these successes are more typical for resident, than anadromous forms of salmonids (Allendorf and Waples, 1996). Unfortunately, some have considered these programs as supplementation, and their success has been transferred or extrapolated into predictions of similar success for the more difficult task of rebuilding depressed populations in the extensively damaged habitats of the Columbia River basin.

The recent NRC report (1996) expressed similar concerns about the use of supplementation. The NRC panel recommended the term "supplementation" be abandoned as a goal of hatcheries. They also concluded that hatcheries were not a proven technology for achieving sustained increases in adult salmon production and their use has had adverse effects on natural salmon populations. Moreover, supplementation, which has multiple and often incompatible definitions in the literature, has generated confusion and uncertainty about appropriate roles for hatcheries. An emerging consensus (Putz and Chairs), 1994; White et al., 1995; National Research Council, 1996) calls for new roles for hatcheries which are tied to rehabilitation or restoration goals of the specific watershed where the hatchery is located. The new roles for hatcheries should be based on and consistent with the conceptual foundation described in our Review of Science.

The NRC (1996) further recommended that hatcheries should be considered an experimental treatment in an integrated regional rebuilding program and should be evaluated accordingly. This is concordant with our review as well. Supplementation will need to be monitored and evaluated on a case-by-case basis for its applicability as a means to accelerate recovery of depressed wild salmonid populations with respect to their abundance and life history diversities. Supplementation may be useful over the short-term to aid in rehabilitating natural populations within the context of an integrated and comprehensive watershed-based restoration approach, that includes an evaluation of the relative risks to the wild population of using versus failing to use supplementation (Hard et al., 1992; Allendorf and Waples, 1996). The proposed chinook salmon supplementation projects in central Idaho appear to follow these guidelines and may be useful as a model for other supplementation projects (Bowles and Leitzinger, 1991).

In implementing the FWP, we advise the Council to resist attempts to implement supplementation on a large scale without adequate planning and review and without adequate monitoring and evaluation in place. Proponents of artificial propagation are often willing to

forgoe adequate monitoring and evaluation and assume success. For example, when mitigation for hydro development in the basin began with implementation of the Lower Columbia River Fisheries Development Program, it was promoted as an action program that could be implemented without delay and research was not needed (Committee 1950). Since then the region has found the need to expend millions of dollars in research on conventional fish culture. Supplementation may prove to be a useful tool in the Columbia Basin for rebuilding depressed stocks in some localities, which in turn could lead to rebuilding of salmon metapopulation structure, but this will only occur if supplementation is approached cautiously in an experimental framework that relies on careful design, rigorous evaluation, and incorporates adaptive management. Within the context of our conceptual foundation, supplementation activities are necessarily temporary, until populations rebuild themselves through natural reproduction. Measurable criteria for the success of the supplementation effort need to be rigorously defined *a priori*, and we advise managers to resist the temptation to increase the scale of goals, designs, and hatchery involvement, if success occurs. If the original goals are biologically sound and realistic, then escalating the goals and hatchery involvement at a later date would be inconsistent with the original supplementation design and may pose significant genetic and demographic risks to the target stock.

Artificial propagation has a 120 year history in the Columbia Basin and an important lesson from that experience should be that the success of new technology applied to fish culture cannot be taken for granted. Each set of local biota, physical conditions and salmon life history type to which supplementation is applied represents the development of new form of aquaculture technology. Each application will be clouded by multiple uncertainties which require careful risk assessment before implementation. Adequate monitoring and evaluation are essential if a supplementation project is implemented. The seriously depleted condition of the resource today calls for quick action, yet the depleted salmon populations in the basin cannot afford to be subjected to new technology without adequate evaluation.

Conclusions (level of proof)

1. Artificial propagation has failed to achieve the objective of replacing natural production lost because of habitat degradation in the basin (1);
2. Belief in the efficacy of artificial propagation led to disproportionate budgets for habitat protection and restoration (3);
3. In the 120 year history of the artificial propagation in the Columbia Basin, the program has never been subjected to a comprehensive evaluation (1);
4. The ecological, behavioral, and energetic interactions of hatchery fish with native species (including wild salmon) and fish assemblages of the Columbia River ecosystem have not been evaluated. In the operation of hatcheries, those interactions are generally assumed to be inconsequential or benign (3);
5. The extent to which the artificial propagation program has implemented relevant research, particularly where the interaction between natural and artificially propagated fish is concerned, has been slow (3);
6. Hatchery operations including broodstock selection, interbasin transfers and release practices have contributed to the decline of natural production and loss of locally adapted stocks in the basin (2);
7 .Management of fisheries on mixed hatchery and wild stocks have contributed to the decline of natural production in the Columbia Basin (2);
8. Because of the declining natural production in the Columbia Basin, those fisheries that still harvest Columbia River salmon are largely supported by the hatchery program (1);
9. Hatchery practices are one of the factors that have altered the genetic structure of stocks in the basin (1).
10. In instances where hatchery broodstock have been derived from local wild stocks that are presently severely depressed, the hatchery stock may contain a significant portion of the genetic diversity of the indigenous stock,. If so, and these populations need to be evaluated to address these concerns, the hatchery population may be an essential element for rebuilding abundance and natural production in the depressed indigenous stock (4).

Uncertainties

1. A major uncertainty stems from the question, can we integrate natural and artificial production systems in the same basin to achieve sustainable long term productivity?
2. The conservation hatchery and captive brood technology are new concepts and roles for artificial propagation. Their use to restore depleted salmon populations should be approached with extreme caution and must be accompanied with a well designed and adequately funded M&E program.
3. A major uncertainty associated with the use of supplementation is the condition of the habitat that will receive the juvenile salmon. Is the habitat capable of supporting salmon at levels of survival that will bring about restoration?

Recommendations

1. Use of artificial propagation to restore depleted salmon populations should be preceded by an assessment of the risks, and supplementation applications must be accompanied with a well designed and adequately funded M&E program.
2. There are three questions that need to be answered in evaluating the hatchery program: Do the artificially propagated fish contribute to the fishery and/or escapement and is the economic benefit of that contribution greater than its cost? Has the program achieved its objective; i. e., has it replaced lost natural production if it is a mitigation hatchery? Has the operation of the hatchery incurred costs to natural production? The first and the third questions are related in that a meaningful cost-benefit analysis should include ecological costs.

Most evaluations of hatchery programs, when they have been carried out, attempted to answer the first question. Information needed to answer the second and third questions has in most cases not collected or has been of poor quality. The FWP should require evaluation which adequately answers all three questions for all funded hatcheries.

3. The FWP should include a valid comprehensive evaluation of the role of artificial propagation in the Columbia Basin. The evaluation should cover the entire 120-year history of the program and include direct and indirect, positive and negative effects. For example, the evaluation should include a discussion of the role that heavy reliance on hatcheries has had on habitat degradation in the tributaries and mainstems and the contribution of hatcheries to the extinction and depletion of naturally producing stocks in the basin. The comprehensive evaluation should also include an assessment of the adequacy of existing monitoring to answer ecological questions.

4. The FWP should include as a separate measure a comprehensive evaluation of the mitigation hatcheries in the basin. What were their objectives, did they achieve their objectives, and if not, why not?
5. The region needs to develop an interim policy regarding the operation and harvest management of production from each hatchery where monitoring has been inadequate to complete a comprehensive evaluation. The interim policy should be designed to minimize the ecological costs of the hatchery until the evaluation can be carried out.
6. The objectives of each hatchery need to be evaluated and redefined if necessary. The objectives should be established within the contexts of the subbasin where the hatchery operates, and our conceptual foundation with particular reference to rebuilding of populations and metapopulations. The hatchery's objectives need to be integrated and defined by the rebuilding objectives of the subbasin. The objectives should consider nontarget species and the existence of metapopulation structure of the target species.
7. Artificial propagation must be treated as an experiment, with hypotheses related to uncertainties, experimental design, analysis, and integration of results with available knowledge consistent with the adaptive management provisions of the FWP.
8. The decision about when and where to use supplementation programs should take into account the principles of the metapopulation concept.
9. Existing hatchery populations may prove to be valuable genetic resources in the future and may prove useful in programs that attempt to rebuild salmon populations and metapopulation structure in the basin.
10. Hatchery populations should be evaluated for evidence of selection, and changes in fitness or genetic diversity associated with residence in the hatchery environment.

D. Infectious Diseases

In 1991, as the Scientific Review Group, we conducted a review for BPA and CBFWA of the Fish Disease Work Plan developed by the Technical Working Group on Fish Disease. We were assisted in the review by Dr. John Schachte, who had been chairman of the Fish Health Section of the American Fisheries Society. Our review was undertaken from the standpoint of how fish disease might affect the council's doubling goal, and provided comments about the Work Plan and associated research priorities (SRG Report 91-4, August, 1991). The following comments are drawn from that review.

The Fish Disease Work Plan and the Fish Disease Technical Working Group did a good job of identifying problem pathogens of salmon in the Columbia Basin, and of focusing research efforts toward understanding and control of those pathogens. The Fish Disease Work Plan and the Fish Disease Technical Working Group appeared to follow groundwork laid down by the Pacific Northwest Fish Health Committee, which by 1984 had developed policy statements on fish disease and was acting as a coordinating entity for research and information exchange on fish disease within the region. In our review, we were particularly complimentary of the Fish Disease Work Plan with respect to three features that were apparent: 1) the sharply focused research objectives stated in the Work Plan; 2) the prioritization process used by the Fish Disease Technical Working Group to rank the research priorities; and 3) the implementation of an annual peer review process to assess progress and modify research objectives, where appropriate. We pointed to the need for periodic updating of the Work Plan to refocus research efforts and priorities as new information is gained.

In setting priorities, the TWG made an assessment of the relative importance of each pathogen in terms of its effects on survival of salmon in hatcheries. However, there is no way of evaluating the efficacy of research on fish disease in terms of its potential to produce more returning adults, unless policy makers are willing to make some broad assumptions that have little or no foundation in experience or documentation. This problem is not unique to the fish disease arena, but is common to the measures in the FWP. Nevertheless, it ought to be possible to assess to some degree what gains in hatchery production might be expected from development of control measures for each pathogen. A beginning was made with BPA's Fish Health Monitoring Program, which extended over five years and gathered information on mortalities of salmon within hatcheries and assigned a cause.

One critical uncertainty in this area is the lack of virtually any information on the impact on wild fish of release of pathogen-infected fish from hatcheries. Policies established by the Pacific Northwest Fish Health Committee are designed to prevent the spread of pathogens that might

result from release of seriously infected hatchery fish. The policy calls for destruction of fish infected with such serious pathogens as IHN, for example. Realistically, it is impossible to rear fish in a hatchery and release them with assurance that they are 100% free of pathogens. We were informed that all of the diseases diagnosed in hatchery settings had also been observed in the wild, but with lower frequencies, as a general rule.

Our review pointed to the fact that fish disease research in the basin has focused on microbiological and immunological characteristics of the disease agents. These approaches are intended to lead to development of specific treatments once an agent is determined to be present. We observed that it would be desirable, in addition to that approach, to consider development of preventive measures, by which we meant to consider the effects of the environment on the incidence of disease. By environment, we meant all of the physical characteristics of the hatcheries and of the natural waters themselves, such as loading densities of fish in the raceways, water quality in the hatcheries and streams, and other factors. There needs to be better coordination between groups investigating hatchery effectiveness, whose responsibility encompasses the environmental factors, and those investigating fish disease. Stress produced by unfavorable environment can lead to susceptibility to disease. Furthermore, certain environmental conditions can favor the pathogens.

Outside of the hatchery, disease-induced mortality may be increased by stressful activities associated with transportation, bypass, altered thermal regimes, and fish marking and recapture procedures. The communicability of Bacterial Kidney Disease has been established (Pascho et al., 1993). This has given rise to concern that crowding of fish in the transportation barges my facilitate the transfer of pathogens among fish within the barges.

NPPC Provisions on Fish Disease

The 1984 FWP included measures 704(h)(2)(D) and 704(h)(2)(E), which referred to the policy statement of the PNFHPC and called upon BPA to fund development of programs to prevent the introduction of fish diseases into the Columbia Basin, prevent the spread of existing diseases, improve fish culture, minimize the impact of fish diseases on wild and cultured stocks, and improve the detection, diagnosis and control of fish diseases and parasites. These provisions are repeated in Section 703(e)(4) of the 1987 FWP. The 1994 FWP includes a fish health policy at Section 7.2A.6, which calls for hatchery practices and operations that will preclude the introduction and/or spread of any fish disease within the Columbia Basin, and maximize the health of fish released from hatcheries.

Fish Disease Impacts

The Fish Disease Technical Working Group established a set of criteria to be used in setting priorities for research on fish disease. The highest priority was given to diseases for which no control (below the threshold of management significance) had been established, ability of the disease to cause morbidity and mortality, significance of the fish affected by the disease, and significance of fishery management constraints caused by the disease. Using these criteria, eight diseases were identified as the most important. They were:

1) Bacterial kidney disease (BKD),
2) Infectious hematopoietic necrosis (IHN),
3) Erythrocytic inclusion body syndrome (EIBS),
4) Fungal disease of adult salmon and their eggs,
5) Ceratomyxosis caused by *Ceratomyxa shasta*,
6) Whirling disease caused by *Myxobolus cerebralis*,
7) Bacterial coldwater disease (BCWD), and
8) *Ichtyoptherius* and *Ichtyobodo* gill and skin parasites.

The following information was taken from the Fish Disease Work Plan developed by the Fish Disease Technical Working Group in 1987.

1) Bacterial Kidney Disease. Spring chinook are extremely vulnerable to BKD. Losses as high as 80% can occur in hatcheries. The disease can be spread from parent to progeny, and disinfection of eggs has little effect. BKD can be spread from wild fish to hatchery fish through water intakes. Reuse of hatchery water, crowding, handling and marking, and transportation all can spread infections. The antibiotic erythromycin can slow losses to BKD, but it seldom cures the outbreak. Permits for use of erythromycin must be renewed annually. Attempts are being made to develop a vaccine.

2) Infectious Hematopoietic Necrosis (IHN). Losses among steelhead and rainbow trout from IHN may range from 30 to 95%. Severe culling procedures are used to limit its spread. A primary concern is that the disease may be adapting from steelhead and rainbow trout to become a threat to spring or summer chinook. To date, few chinook have died from IHN, but millions of eggs have been destroyed to eliminate the possibility of transmission. Attempts are being made to develop a vaccine.

3) Erythrocytic Necrosis Inclusion Body Syndrome (EIBS). This disease leads to severe anemia among chinook. Little is known about this disease, other than that it is caused by a virus. No treatment is available. Much remains to be learned about transmission, sources of infection, pathogenicity and diagnostic methods.

4) Fungus. The further upstream that chinook are observed, the more heavily they are infested with fungus. This is a particular problem in hatchery ponds where adults are held before they are ripe and ready for spawning. Left untreated in the holding ponds, fungus can kill 50 to 80% of spring chinook adults prior to spawning. Malachite green was formerly the treatment of choice, however, its use was not permitted after 1989, due to its implication in causing cancer in laboratory animals.

5) Ceratomyxosis. The causative agent of this disease, *Ceratomyxa shasta*, is most abundant in the lower Columbia, the Deschutes, and Willamette rivers. *Ceratomyxa* is seldom a cause of losses in hatcheries, but outmigrating wild and hatchery smolts are thought to encounter losses as they pass through the lower river that may range as high as 15%, depending on migration timing and environmental conditions. No treatments are available.

6) Whirling Disease. This disease, caused by a protozoan parasite, *Myxobolus cerebralis*, was not known to occur in the Columbia Basin until 1986. At the time of its first discovery in the basin, the NPFHPC listed it as an emergency pathogen. It was first recorded in domestic rainbow trout and wild steelhead and chinook in several streams in northeastern Oregon. It has subsequently (1995) been reported from Montana and Colorado, where it has been implicated in sudden sharp declines in native trout numbers. Basic information is urgently needed on the relationship between the pathogen and its hosts.

7) Bacterial Coldwater Disease (BCWD). BCWD has many of the same characteristics as BKD. Its greatest impact is on sac fry and young fingerlings, just beginning to feed. Effective therapeutic agents are being sought for this internal infection.

8) *Ichthyoptherius* and *Ichthyobodo*. *Ichthyoptherius* is perhaps the most common cause of losses of young salmon in their incubators or raceways. *Ichthyobodo* infects the gills of juveniles. When numerous on the gills of smolts, saltwater adaptation of the fish can be difficult or impossible. Treatment formerly consisted of formalin or malachite green. New treatments were being sought in 1991.

Literature Cited

Allendorf, F.W. 1991. Ecological and genetic effects of fish introductions: synthesis and recommendations. Canadian Journal of Fsheries and Aquatic Sciences 48, Supplemental 1: 178-181.

Allendorf, F.W. and R.F. Leary. 1988. Conservation and distribution of genetic variation in a polytypic species, the cutthroat trout. Conserv. Biol. 2: 170-184.

Allendorf, F.W. and S.R. Phelps. 1980. Loss of genetic variation in a hatchery stock of cutthroat trout. Transactions of the American Fisheries Society 109: 537-543.

Allendorf, F.W. and N. Ryman. 1987. Genetic management of hatchery stocks. Population genetics and fishery management. N. Ryman and F. Utter. Seattle, Washington, University of Washington Press**:** 141-160.

Allendorf, F.W. and F.M. Utter. 1979. Population genetics. Fish Physiol. 8: 407-454.

Allendorf, F.W. and R.S. Waples. 1996. Conservation and genetics of salmonid fishes. Conservation genetics: Case histories from nature. J. C. Avise, Chapman Hall**:** 238-280.

Ayerst, J.D. 1977. The role of hatcheries in rebuilding steelhead runs of the Columbia River system. Columbia River Salmon and Steelhead, March 5-6, 1976, American Fish. Soc., Washington, DC.

Bartley, D.M., G.A.E. Gall and B. Bentley. 1990. Biochemical genetic detection of natural and artifical hybridization of chinook and coho salmon in northern California. Trans. Amer. Fish. Soc. 119: 431-437.

Beaty, R.E. 1992. Changes in size and age at maturity of Columbia River upriver bright fall chinook salmon (*Oncorhynchus tshawytscha*): Implications for stock fitness, commercial value, and management. Corvallis, Oregon State University. Oregon**:** 270.

Beverton, R.J.H. and S.J. Holt. 1957. On the dynamics of exploited fish populations, Minist. Mar. Fish. and Minist. Agric. Fish Food (G.B.).

Bilby, R.E., B.R. Fransen and P.A. Bisson. 1996. Incorporation of nitrogen and carbon from spawning coho salmon in the trophic system of small streams: evidence from stable isotopes. Canadian Journal of Fisheries and Aquatic Sciences 53: 164-173.

Bottom, D.J. In Press. To till the water: A history of ideas in fisheries conservation. Pacific Salmon and Their Ecosystems. D. J. Stouder, P. A. Bisson and R. J. Naiman. New York, Chapman and Hall.

Bowles, E. 1993. Operation of Compensation Hatcheries within a Conservation Framework. Boise, Idaho Dept. of Fish and Wildlife. Idaho.

Bowles, E. and E. Leitzinger. 1991. Salmon supplementation studies in Idaho Rivers (Idaho supplementation studies), Experimental design. Portland, USDOE, Bonneville Power Administration. Oregon**:** 132+.

Bowles, E.C. 1995. Supplementation: panacea or curse for recovery of declining fish stocks. Uses and effects of cultured fishes in aqautic ecosystems. H. L. Schramm and R. G. Piper. Bethesda, MD, American Fisheries Soociety Symposium. 15**:** 277-283.

Busack, C.A. and K.P. Currens. 1995. Genetic risks and hazards in hatchery operations: fundamental concepts and issues. Uses and effects of cultured fishes in aqautic ecosystems. H. L. Schramm and R. G. Piper. Bethesda, MD, American Fisheries Soociety Symposium. 15**:** 71-80.

Campton, D.E. 1995. Genetic effects of hatchery fish on wild populations of Pacific salmon and steelhead: What do we really know? American Fisheries Society Symposium 15: 337-353.

Campton, D.E. and J.M. Johnston. 1985. Electrophoretic evidence for a genetic admixture of native and nonnative rainbow trout in the Yakima River, Washington. Trans. Amer. Fish. Soc. 114: 782-793.

Campton, D.E. and F.M. Utter. 1985. Natural hybridization between steelhead trout (Salmo gairdneri) and coastal cutthroat trout (Salmo clarki clarki) in two Puget Sound streams. Can. J. Fish. Aquat. Sci. 42(1): 110-119.

Chapman, D., A. Giorgi, M. Hill, A. Maule, S. McCutcheon, D. Park, W. Platts, K. Pratt, J. Seeb, L. Seeb and F. Utter. 1991. Status of Snake River Chinook Salmon. Boise, Don Chapman Consultants, Inc., 3653 Rickenbacker, Suite 200. Idaho**:** 520.

Chapman, D., A. Giorgi, T. Hillman, D. Deppert, M. Erho, S. Hays, C. Peven, B. Suzumoto and R. Klinge. 1994. Status of Summer/Fall Chinook Salmon in the Mid-Columbia Region. Boise, Don Chapman Consultants Inc. Idaho**:** 411 + app.

Chapman, D.W. 1986. Salmon and steelhead abundance in the Columbia River in the nineteenth century. Trans. Am. Fish. Soc. 115: 662-670.

Cobb, J.N. 1930. Pacific Salmon Fisheries. Washington, Bureau of Fisheries. District of Columbia.

Columbia Basin Fish and Wildlife Authority. 1990. Review of the history, development, and management of anadromous fish production facilities in the Columbia River Basin. Portland, Columbia Basin Fish and Wildlife Authority and U.S. Fish & Wildlife Service. Oregon**:** 52.

Comm., O.F.a.G. 1919. Biennial Report of the Fish and Game Commission of the State of Oregon to the Governor and the Thirtieth Legislative Assembly, 1919. Salem, State of Oregon. Oregon.

Commissioners, O.B.o.F. 1888. First Report of the State Board of Fish Commissioners to the Governor of Oregon. Salem. Oregon.

Craig, J.A. and R.L. Hacker. 1940. The history and development of the fisheries of the Columbia River. U.S. Bureau of Fisheries Bulletin 32: 133-216.

Craig, O.J. 1899. University of Montana Summer School of Science and First Summer Opening of the Montana Biological Station., University of Montana, Missoula.

Cuenco, M.L., T.W.H. Backman and P.R. Mundy. 1993. The use of supplementation to aid in natural stock restoration. Genetic Conservation of Salmonid Fishes. J. G. Cloud and G. H. Thorgaard. New York, Plenum Press**:** 269-293.

Culler, C.F. 1932. Progress in fish culture. Trans. Amer. Fish. Soc.: 114-118.

Currens, K.P., C.B. Schreck and H.W. Li. 1990. Allozyme and morphological divergence of rainbow trout (*Oncorhynchus mykiss*) above and below waterfalls in the Deschutes River, Oregon. Copeia 1990: 730-746.

Cushing, D.H. 1983. Key Papers on Fish Populations. Washington, IRL Press Limited.

Darwin, C. 1859. The Origin of Species by Means of Natural Selection. New York, The Modern Library.

Delarm, M.R., E. Wold and R.Z. Smith. 1989. Columbia River Fisheries Development Program Fishways and Stream Improvement Projects. Seattle, NMFS/NOAA. Washington.

DeLoach, D.B. 1939. The salmon canning industry. Oregon State Monographs Economic Studies No. 1.

Doppelt, B., M. Scurlock, C. Frissell and J. Karr. 1993. Entering the Watershed: A New Approach to Save America's River Ecosystems. Covelo, CA, Island Press.

Ebel, W.J. 1977. Panel 2: Fish passage problems and solutions, major passage problems. Columbia River Salmon and Steelhead, March 5-6, 1976, American Fisheries Soc., Washington, DC.

Eggers, D.M. 1992. The costs and benefits of the management program for natural sockeye salmon stocks in Bristol Bay, Alaska. Fisheries Research 14: 159-177.

Emlen, J.M. 1991. Heterosis and outbreeding depression: a multi-locus modle and an application to salmon production. Fisheries Research 12: 187-212.

Eriksson, T. and L.-O. Eriksson. 1993. The status of wild and hatchery propagated Swedish salmon stocks after 40 years of hatchery releases in the Baltic rivers. Fisheries Research 18(1993): 147-159.

Fausch, K.D. 1988. Tests of competition between native and introduced salmonids in streams: what have we learned. Can. J. Fish. Aquat. Sci. 45(12): 2238-2246.

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest Ecosystem Management: An Ecological, Economic, and Social Assessment. Portland, Interagency Supplemental Envir. Impact Statement Team. Oregon.

Fish, F.F. and M.G. Hanavan. 1948. A Report upon the Grand Coulee Fish-Maintenance Project 1939-1947. Washington, US Fish and Wildlife Service. District of Columbia.

Flagg, T.A., C.V.W. Mahnken and K.A. Johnson. 1995. Captive broodstocks for the recovery of Snake River sockeye salmon. Uses and effects of cultured fishes in aqautic ecosystems. H. L. Schramm and R. G. Piper. Bethesda, MD, American Fisheries Soociety Symposium. 15**:** 81-90.

Flagg, T.A., F.W. Waknitz, D.J. Maynard, G.B. Milner and C.V.W. Mahkhen. 1995. The effect of hatcheries on native coho salmon populations in the lower Columbia River, Symposium 15. Uses and Effects of Cultured Fishes in Aquatic Ecosystems, American Fisheries Society, Bethesda, MD.

Foerster, R.E. 1936. Sockeye salmon propagation in British Columbia. Ottawa, Biological Board of Canada. Ontario, Canada.

Forbes, S.H. and F.W. Allendorf. 1991. Associations between mitochondrial and nuclear genotypes in cutthroat trout hybrid swarms. Evolution 45(6): 1332-1349.

Fried, S.M. and H.J. Yuen. 1987. Forecasting sockeye salmon (*Oncorhynchus nerk*a) returns to Bristol Bay, Alaska: a review and critique of methods. Sockeye Salmon (*Oncorhynchus nerka*) Population Biology and Future Management, Canadian Special Publication in Fisheries and Aquatic Sciences. H. D. Smith, L. Margolis and C. Wood. 96**:** 273-279.

Frissell, C.A. 1993. Topology of extinction and endangerment of native fishes in the Pacific northwest and California (U.S.A.). Conservation Biology 7(2): 342-354.

Frissell, C.A. and D. Bayles. 1996. Ecosystem management and the conservation of aquatic biodiversity and ecological integrity. J. Amer. Water Res. Assoc. 32(2): 229-240.

Frissell, C.A., W.J. Liss and D. Bayles. 1993. An integrated, biophysical strategy for ecological restoration of large watersheds. Proceedings of the Symposium on Changing Roles in Water Resources Management and Policy. N. E. Spangenborg and D. E. e. Potts. Bethesda, American Water Resources Association**:** 449-456.

Frissell, C.A. and R.K. Nawa. 1992. Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. North American Journal of Fisheries Management 12: 182-197.

Game, W.D.o.F.a. 1904. Fourteenth and Fifteenth Annual Report of the State Fish Commissioner to the Governor of the State of Washington. Seattle. Washington.

Gausen, D. 1993. The Norwegian gene bank programme for Atlantic Salmon (*Salmo salar*). Genetic conservation of salmonid fishes. J. G. Cloud and G. H. Thorgaard. New York, Plenum Press. 248**:** 181-188.

General Accounting Office. 1992. Endangered Species: Past Actions Taken to Assist Columbia River Salmon. Washington. District of Columbia.

Gharrett, A.J. and W.W. Smoker. 1991. Two generations of hybrids between even- and odd-year pink salmon (Oncorhynchus gorbuscha): a test for outbreeding depression? Canadian Jouornal of Fisheries and Aquatic Sciences 48(9): 1744-1749.

Gharrett, A.J. and W.W. Smoker. 1993. Genetic components in life history traits contribute to population structure. Genetic conservation of salmonid fishes. J. G. Cloud and G. H. Thorgaard. New York, Plenum Press. 248**:** 197-202.

Goode, G.B. 1884. The Status of the US Fish Commission in 1984. Part XLI in Part XII. Washington, US Commission of Fish and Fisheries. DC.

Gottschalk, J. 1942. Report of the division of fish culture. Trans. Amer. Fish. Soc., Seventy-first Annual Meeting, August 25-26, 1941.

Hard, J.J., R.P. Joness, M.R. Delarm and R.S. Waples. 1992. Pacific salmon and aritificial propagation under the Endangered Species Act, U. S. Dept. Commer.,.

Hayden, M.V. 1930. History of the Salmon Industry of Oregon. Eugene, University of Oregon. Oregon.

Hedgepeth, J.W. 1941. Livingston Stone and fish culture in California. California Fish and Game 27(3): 126.

Heggberget, T.G., B.O. Johnsen, K. Hindar, B. Jonsson, L.P. Hansen, N.A. Hvidsten and A.J. Jensen. 1993. Interactions between wild and cultured Atlantic salmon: a review of the Norwegian experience. Fisheries Research 18: 123-146.

Hilborn, R. 1987. Living with uncertainty in resource management. North American Journal of Fisheries Management 7: 1-5.

Hilborn, R. 1992. Hatcheries and the future of salmon in the Northwest. Fisheries 17(1): 5.

Hilborn, R. and C.J. Walters. 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. New York, Chapman & Hall.

Hilborn, R. and J. Winton. 1993. Learning to enhance salmon production: lesson from the Salmonid Enhancement Program. Can. J. Fish. Aquat. Sci. 50.

Hile, R. 1936. The increase in the abundance of the yellow pike-perch, (*Stizostedion vitreum* (Mitchill)), in lakes Huron and Michigan, in relation to the artificial propagation of the species. The Collected Papers of Ralphe Hile, 1928-73. Washington, US Dept. of Interior, Fish and Wildlife Service**:** 143-159.

Hindar, K., N. Ryman and F. Utter. 1991. Genetic effects of cultured fish on natural fish populations. Canadian Journal of Fisheries and Aquatic Sciences 48(Supplement 1): 945-957.

Hunter, C.J. 1991. Better Trout Habitat: A Guide to Stream Restoration and Management. Washington, Island Press.

Huntsman, A.G. 1937. Races and homing of salmon. Science 85: 477-478.

Jensen, T.C. 1986. The United States-Canada Pacific salmon interception treaty: an historical and legal overview. Environmental Law 16(3): 363-422.

Johnson, D.R., W.M. Chapman and R.W. Schoning. 1948. The Effects on Salmon Populations of the Partial Elimination of Fixed Fishing Gear on the Columbia River in 1935. Portland, Oregon Fish Commission. Oregon.

Johnson, S.L. 1984. Freshwater Environmental Problems and Coho Production in Oregon. Corvallis, Oregon Dept. of Fish and Wildlife. Oregon.

Kauffman, J.B., R.L. Case, D. Lytjen, N. Otting and D. Cummings. 1995. Ecological approaches to riparian restoration in northeast Oregon. Restoration and Management Notes 13: 12-15.

Kostow, K. 1995. Biennial Report of the Status of Wild Fish in Oregon. Portland, Oregon Dept. of Fish and Wildlife. Oregon.

Krueger, C.C. and B. May. 1991. Ecological and genetic effects of salmonid introductions in North America. Canadian Journal of Fisheries and Aquatic Sciences 48(Supplement 1): 66-77.

Kyle, G.B., J.P. Koenings and B.M. Barrett. 1988. Density-dependent, trophic level responses to an introduced run of sockeye salmon (*Oncorhynchus nerka*) at Frazer Lake, Kodiak Island, Alaska. Can. J. Fish. Aquat. Sci. 45: 856-867.

Lande, R. 1988. Genetics anad demography in biological conservation. Science 241: 1455-1460.

Lande, R. and G.F. Barrowclough. 1987. Effective population size, genetic variation, and their use in population management. Viable Populations for Conservation. M. E. Soule. New York, Cambridge University Press**:** 87-124.

Lavier, D.C. 1976. Major Dams on Columbia River and Tributaries. Olympia, Washington Dept. of Game. Washington.

Laythe, L.L. 1948. The fishery development program in the lower Columbia River. American Fisheries Society, Atlantic City, New Jersey, Amer. Fish. Soc.

Leary, R.F., F.W. Allendorf and K.L. Knudsen. 1985. Developmental instability as an indicator of related genetic variation in hatchery trout. Trans. Amer. Fish. Soc. 114: 230-235.

Leary, R.F., F.W. Allendorf and G.K. Sage. 1995. Hybridization and introgression between introduced and native fish. Uses and effects of cultured fishes in aqautic ecosystems. H. L. Schramm and R. G. Piper. Bethesda, MD, American Fisheries Soociety Symposium. 15**:** 91-101.

Lichatowich, J. and J.D. McIntyre. 1987. Use of hatcheries in the management of anadromous salmonids. American Fisheries Society Symposium 1: 131-136.

Lichatowich, J. and B. Watson. 1993. Use of Artificial Propagation and Supplementation for Rebuilding Salmon Stocks Listed Under the Endangered Species Act. Portland, Bonneville Power Administration. Oregon**:** 103.

Lichatowich, J.A. and J. Nicholas. In press. Oregon's first century of hatchery intervention in salmon production: Evolution of the hatchery program, legacy of a utilitarian philowophy and management recommendations. International Symposium on Biological Interactions of Enhanced and Wild Salmonids, June 17-20, 1991, Nanaimo, British Columbia.

Maitland, J.R.G. 1884. The culture of salmonidae and the acclimatization of fish. The Fisheries Exhibition Literature, International Fisheries Exhibition, London, 1883. London, William Clowes and Sons, Limited.

Mathisen, O.A. 1972. Biogenic enrichment of sockeye salmon and stock productivity. Verh. Int. Ver. Limnol. 18: 1089-1095.

McAllister, M.K. and R.M. Peterson. 1992. Experimental design in the management of fisheries: a review. N. Amer. J. Fish. Mgt. 12(1): 1-18.

McDonald, M. 1894. The salmon fisheries of the Columbia River basin. Report of the Commissioner of Fish and Fisheries Investigations in the Columbia River Basin in Regard to the Salmon Fisheries. Senate Miscellaneous Document No. 200, 53rd Congress 2d Session, and House Miscellaneous Document No. 86, 53d Congress, 3d Session**:** 3-18.

McGurrin, J., D. Ubert and D. Duff. 1995. Use of cultured salmonids in the federal aid in sport fish restoration program. Amer. Fish. Soc. Symp. 15: 12-15.

Meffe, G.K. 1992. Techno-arrogance and halfway technologies: salmon hatcheries on the Pacific coast of North America. Conservation Biology 6(3): 350-354.

Messmer, R.T., R.W. Carmichael, M.W. Flesher and T.A. Whitesel. 1992. Evaluation of Lower Snake River Compensation Plan Facilities in Oregon. Portland, Oregon Dept. of Fish and Wildlife. Oregon.

Mighetto, L. and W.J. Ebel. 1994. Saving the Salmon: A History of the US Army Corps of Engineers. Efforts to Protect Anadromous Fish on the Columbia and Snake Rivers. Seattle, Historical Research Associates.

Miller, R.B. 1957. Have the genetic patterns of fishes been altered by introductions or selective fishing? Journal of the Fisheries Research Board of Canada 14: 797-806.

Miller, W., C. Steward and T. Bjornn. 1990. Analysis of Salmon and Steelhead Supplementation, Parts 1-3. Portland, Bonneville Power Administration. Oregon.

Moore, E. 1925. Report of the Vice President Division of Fish Culture, New York State Conservation Commission. Trans. of the Amer. Fish. Soc. Fifty-fifth Annual Meeting, American Fisheries Society, Denver.

Muir, W.D.a.t.c. 1996. Survival Estimates for the Passage of Yearling Chinook Salmon and Steelhead through Snake River Dams and Reservoirs, 1995 (draft). Seattle, Northwest Fisheries Science Center, National Marine Fisheries Service. Washington.

Mullan, J.W., A. Rockhold and C.R. Chrisman. 1992. Life histories and precocity of chinook salmon in the Mid-Columbia River. Progressive Fish-Culturist 54(1): 25-28.

Mundy, P.R. 1985. Harvest control systems for commercial marine fisheries management; theory and practice. Fisheries Dynamics, Harvest Management and Sampling, Washington Sea Grant Technical Report 85-1. P. R. Mundy, a. T. J. Quinn and R. B. Deriso. Seattle, University of Washington.

Mundy, P.R. in press. The role of harvest management in determining the status and future of Pacific salmon populations: Shaping human behavior to enable the persistence of salmon.

Pacific Salmon and Their Ecosystems: Status and Future Options. R. J. N. a. D. Stouder. New York, USA, Chapman Hall.

Mundy, P.R., T.W.H. Backman and J. Berkson. 1995. Experiences from the Columbia River. Defining Conservation Units for Endangered Species. J. M. Nielsen. Bethesda, American Fisheries Society.

Mundy, P.R. and O.A. Mathisen. 1981. Abundance estimation in a feedback control system applied to the management of a commercial salmon fishery. Applied Operations Research in Fishing. K. B. Haley. New York, Plenum Publishing Corp.**:** 81-98.

National Marine Fisheries Service. 1995. Proposed Recovery Plan for Snake River Salmon. Washington, US Dept. of Commerce, National Oceanic and Atmospheric Administration. District of Columbia**:** 387.

National Research Council. 1995. Science and the Endangered Species Act. Washington, National Academy Press.

National Research Council. 1996. Upstream: salmon and society in the Pacific Northwest. Report on the Committee on Protection and Management of Pacific Northwest Anadromous Salmonids for the National Research Council of the National Academy of Sciences. Washington D. C., National Academy Press.

Needham, P.R. 1939. Natural propagation versus artificial propagation in relation to angling. Fourth North American Wildlife Conference, February 13-15, American Wildlife Institute, Washington.

Nehlsen, W., J.E. Williams and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: Stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2): 4-21.

Netboy, A. 1974. The Salmon Their Fight for Survival. Boston, Houghton Mifflin Co.

Nickelson, T.E., M.F. Solazzi and S.L. Johnson. 1986. Use of hatchery coho salmon (Oncorhynchus kisutch) presmolts to rebuild wild populations in Oregon coastal streams. Can. J. Fish. Aquat. Sci. 43(12): 2443-2449.

Northwest Power Planning Council. 1992. Columbia River Basin Fish and Wildlife Program. Portland. Oregon.

Northwest Power Planning Council. 1992. Strategy for Salmon, Vol. 1. Portland, Northwest Power Planning Council. Oregon**:** 43.

Northwest Power Planning Council. 1992. Strategy for Salmon, Vol. 2. Portland, Northwest Power Planning Council. Oregon**:** 98.

Northwest Power Planning Council. 1994. 1994 Columbia River Basin Fish and Wildlife Program. Portland, Northwest Power Planning Council. Oregon.

Northwest Power Planning Council. 1994. Columbia River Basin Fish and Wildlife Program. Portland. Oregon.

Office, G.A. 1993. Endangered species: potential economic costs of further protection for Columbia River salmon. Washington, U. S. General Accounting Office. DC**:** 34.

Olson, D.E., B.C. Cates and D.H. Diggs. 1995. Use of a national fish hatchery to complement wild salmon and steelhead production in an Oregon stream. Amer. Fish. Soc. Symp. 15: 317-328.

Oregon Fish Commission. 1933. Biennial Report of the Fish Commission of the State of Oregon to the Governor and the Thirty-seventh Legislative Assembly, 1933. Salem, State of Oregon. Oregon.

Ortmann, D.W., F. Cleaver and K.R. Higgs. 1976. Artificial Propagation. Portland, Pacific Northwest Regional Commission.

Pascho, R.J., D.G. Elliott and S. Achord. 1993. Monitoring of the in-river migration of smolts from two groups of spring chinook salmon, *Oncorhynchus tshawytshca* (Walbaum), with different profiles of *Renibacterium salmoninarum* infection. Aquaculture and Fisheries Management 24: 163-169.

Paulik, G.J. 1969. Computer simulation models for fisheries research, management, and teaching., Trans. Am. Fish. Soc. 98(3):551-559.

Philipp, D.P. and J.E. Clausen. 1995. Fitness and performance differences between two stocks of largemouth bass from different river drainages witin Illinois. Uses and effects of cultured fishes in aqautic ecosystems. H. L. Schramm and R. G. Piper. Bethesda, MD, American Fisheries Soociety Symposium. 15**:** 236-243.

Philipp, D.P., J.M. Epifanio and M.J. Jennings. 1993. Point/Counterpoint: conservation genetics and current stocking practices — are they compatible? Fisheries 18(12): 14-16.

Pielou, E.C. 1969. An introduction to mathematical ecology. New York, John Wiley & Sons.

Putz, B. and F.M.P. Chairs). 1994. U. S. Fish and Wildlife Service National Fish Hatchery Review. Arlington VA, The Conservation Fund, The National Fish and Wildlife Foundation.

Reeves, G.H. and J.R. Sedell. 1992. An ecosystem approach to the conservation and management of freshwater habitat for anadromous salmonids in the Pacific Northwest. Trans. 57th Wildlife and Natural Resources Conference., Washington.

Reisenbichler, R.R. 1995. Questions and partial answers about supplementation -- genetic differences between hatchery fish and wild fish. Columbia River Anadromous Salmonid Rehabilitation Symposium, Richland, Washington.

Reisenbichler, R.R. and J.D. McIntyre. 1977. Genetic differences in growth and survival of juvenile hatchery and wild steelhead trout, *Salmo gairdneri*. Journal of the Fisheries Research Board of Canada 34: 123-128.

Reisenbichler, R.R. and J.D. McIntyre. 1986. Requirements for integrating natural and artificial production of anadromous salmonids in the Pacific Northwest. Fish Culture in Fisheries Management, March 31 - April 3, 1985, Lake Ozark, Missouri.

Reisenbichler, R.R. and J.d. McIntyre. 1986. Requirements for integrating natural and artificial production of anadromous salmonids in the Pacific Northwest. Fish culture in fisheries management. R. H. Stroud. Bethesda, American Fisheries Society**:** 365-374.

Rhodes, J.J., D.A. McCullough and J. F. A. Espinosa. 1994. A Coarse Screening Process for Evaluation of the Effects of Land Management Activities on Salmon Spawning and Rearing Habitat in ESA Consultations. Portland, Columbia River Inter-Tribal Fish Commission. Oregon.

Rich, W.H. 1920. Early history and seaward migration of chinook salmon in the Columbia and Sacramento Rivers. Bulletin of the US Bureau of Fisheries, Washington, DC 37.

Rich, W.H. 1939. Fishery problems raised by the development of water resources. Dams and the Problems of Migratory Fishes, Stanford University, Fish Comm. of State of Oregon.

Rich, W.H. 1941. The present state of the Columbia River salmon resources. Sixth Pacific Science Congress, Berkeley, Fish Comm. of State of Oregon.

Rich, W.H. and H.B. Holmes. 1929. Experiments in marking young chinook salmon on the Columbia River, 1916 to 1927. Bulletin of the Bureau of Fisheries, Washington, DC Document No. 1047.

Ricker, W.E. 1954. Nomenclatorial notes on Plecoptera., Proc. Entomol. Soc. British Columbia 51:37-39.

Ricker, W.E. 1954. Stock and recruitment. J. Fish. Res. Board. Can. 11: 559-623.

Ricker, W.E. 1958. Handbook of Computations for Biological Statistics of Fish Populations. Ottawa, Fisheries Research Board of Canada**:** 300.

Ricker, W.E. 1972. Hereditary and environmental factors affecting certain salmonid populations. The Stock Concept in Pacific Salmon. R. C. Simon and P. A. Larkin. Vancouver, University of British Columbia**:** 19-160.

Ricker, W.E. 1973. Linear regressions in fishery research. J. Fish. Res. Board Can. 30: 409-434.

Ricker, W.E. 1981. Changes in the average size and age of Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 38: 1636-1656.

Ricker, W.E.a.H.D.S. 1975. A revised interpretation of the history of the Skeena River sockeye salmon Oncorhynchus nerka)., J. Fish. Res. Board Can. 32(8):1369-1381.

Riddell, B.E. and W.C. Legget. 1981. Evidence for an adaptive basis variation in body morphology and time of downstream migration juvenile Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 38: 308-320.

Rieman, B.E. and J.D. McIntyre. 1993. Demographic and habitat requirements for conservation of bull trout. Ogden, US Forest Service, Intermountain Research Station. Utah**:** 38.

Roos, J.F. 1991. Restoring Fraser River Salmon. Vancouver, Pacific Salmon Commission. British Columbia, Canada.

Rounsefell, G.A. 1947. The effect of natural and artificial propagation in maintaining a run of Atlantic salmon in the Penobscot River. Trans. Amer. Fish. Soc. 74: 188-208.

Ryman, N. and F. Utter. 1987. Population genetics and fishery management. Seattle, WA, University of Washington Press.

Salo, E.O. and W.H. Bayliff. 1958. Artificial and Natural Production of Silver Salmon, *Oncorhynchus kisutch*, at Minter Creek, Washington. Olympia, Washington Dept. of Fisheries. Washington.

Schalk, R.F. 1986. Estimating salmon and steelhead usage in the Columbia Basin before 1850: the anthropological perspective. Northwest Envir. Journal 2(2): 1-29.

Schramm, H.L. and V. Mudrak. 1994. Essay: beneficial aspects of put-and-take trout stocking. Fisheries 19(8): 6-7.

Schuck, H.A. 1943. Survival, population density, growth and movement of the wild brown trout in Crystal Creek. Transactions of the American Fisheries Society 73: 209-230.

Schwiebert, E. 1977. Some notes on the symposium. Columbia River Salmon and Steelhead, March 5-6, 1976, American Fisheries Society, Washington, DC.

Shoemaker, C.D. and R.E. Clanton. 1923. Biennial Report of the Fish Commission of the State of Oregon to the Governor and the Thirty-second Legislative Assembly, 1923. Salem, State of Oregon. Oregon.

Simms, J. 1877. Letter to the Commissioner of Indian Affairs from J. Simms, U.S. Indian Agent, Colville Agency.

Soule, M.E., Ed. 1987. Viable Populations for Conservation. New York, Cambridge University Press.

Stanford, J.A., J.V. Ward, W.J. Liss, C.A. Frissell, R.N. Williams, J.A. Lichatowich and C.C. Coutant. *in press*. A general protocol for restoration of regulated rivers. Regulated Rivers.

Sterne, J.K. 1995. Supplementation of wild salmon stocks: a cure for the hatchery problem or more hatchery problems? Coastal Management 23: 123-152.

Steward, C.R. and T.C. Bjornn. 1990. Supplementation of salmon and steelehad stocks with hatchery fish: a synthesis of published literature. Analysis of Salmon and Steelhead Supplementation, Parts 1-3. W. H. Miller. Portland, Bonneville Power Administration. Project 88-100.

Stone, L. 1879. Report of operations at the salmon-hatching station on the Clackamas River, Oregon, in 1877. Report of the Commissioner for 1877. Washington, US Commission of Fish and Fisheries**:** Part 11 in Part 5.

Thompson, W.F. 1951. An Outline for Salmon Research in Alaska. Seattle, Fisheries Research Institute, University of Washington. Washington.

Thorpe, J.E. 1995. Impacts of fishing on genetic structure of salmonid populations. Genetic conservation of salmonid fishes. J. G. Cloud and G. H. Thorgaard. New York, Plenum Press. 248**:** 67-80.

Utter, F.M., D.W. chapman and A.R. Marshall. 1995. Genetic population structure and history of chinook salmon of the upper Columbia River. Evolution and the aquatic ecosystem: defining unique units in population conservarion. J. L. Nielsen. Bethesda, Maryland, American Fisheries Society Symposium. 17**:** 149-168.

Van Cleve, R. and R. Ting. 1960. The Condition of Salmon Stocks in the John Day, Umatilla, Walla Walla, Grande Ronde, and Imnaha Rivers as Reported by Various Fisheries Agencies. Seattle, Dept. of Oceanography, University of Washington. Washington.

Van Hyning, J.M. 1973. Factors affecting the abundance of fall chinook salmon in the Columbia River. Research Reports of the Fish Commission of Oregon 4(1).

Van Oosten, J. 1942. Relationship between the plantings of fry and production of whitefish in Lake Erie. American Fisheries Society 71st Annual Meeting, St. Louis, MO.

Vannote, R.L., G.W. Minshall, K. W.Cummins, J.R. Sedell and C.E. Cushing. 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37(1): 130-137.

Wahle, R.J. and R.R. Vreeland. 1978. Bioeconomic contribution of Columbia River hatchery fall chinook salmon, 1961 through 1964 broods, to the Pacific salmon fisheries. Fisheries Bulletin 76(1): 179-208.

Wahle, R.J., R.R. Vreeland and R.H. Lander. 1974. Bioeconomic contribution of Columbia River hatchery coho salmon, 1965 and 1966 broods, to the Pacific salmon fisheries. Fisheries Bulletin 72(1): 139-169.

Wallis, J. 1964. An Evaluation of the Bonneville Salmon Hatchery. Clackamas, Oregon Fish Commission Research Laboratory. Oregon.

Walters, C.J. 1986. Adaptive Management of Renewable Resources. New York, MacMillan Publishing Company.

Walters, C.J. and J.S. Collie. 1988. Is research on environmental factors useful to fisheries management? Canadian Journal of Fisheries and Aquatic Sciences 45: 1848-1954.

Waples, R.S. 1991. Definition of "species" under the endangered species act: Application to pacific salmon. Seattle, National Marine Fisheries Service. Washington**:** 29.

Waples, R.S. 1991. Genetic interactions between hatchery and wild salmonids: lessons from the Pacific Northwest. Can. J. Fish. Aquat. Sci. 48(Suppl. 1): 124-133.

Waples, R.S. and C. Do. 1995. Genetic risk associated with supplementation of Pacific salmonids: captive broodstock programs. Canadian Journal of Fisheries and Aquatic Sciences 51(1): 310-329.

Waples, R.S. and P.E. Smouse. 1990. Gametic disequilibrium analysis as a means of idenitfying mixtures of salmon populations. American Fisheries Society Symposium 7: 439-458.

Waples, R.S., D.J. Teel and P.B. Aebersold. 1991. A genetic evaluation and monitoring program for supplemented populations of salmon and steelhead in the Snake River Basin, National Marine Fisheries Service.

Ware, D.M. and R.E. Thompson. 1991. Link between long-term variability in upwelling and fish production in the northeast Pacific Ocean. Can. J. Fish. Aquat. Sci. 48(12): 2296-2306.

Wash. Dept. of Fisheries, W.D.o.W., and Western Wash. Treaty Indian Tribes. 1993. 1992 Washington State Salmon and Steelhead Stock Inventory. Olympia. Washington.

Washington, P.M. and A.M. Koziol. 1993. Overview of the interactions and environmental impacts of hatchery practices on natural and artificial stocks of salmonids. Fisheries Research 18: 105-122.

White, R.J., J.R. Karr and W. Nehlsen. 1995. Better roles for fish stocking in aquatic resource management. Uses and effects of cultured fishes in aquatic ecosystems.

Williams, R.N., D.K. Shiozawa, J.E. Carter and R.F. Leary. 1996. Genetic detection of putative hybridization between native and introduced rainbow trout populations of the Upper Snake River. Transactions of the American Fisheries Society 125: 387-401.

Winton, J. and R. Hilborn. 1994. Lessons from the supplementation of chinook salmon in British Columbia. N. Amer. J. Fish. Mgmt. 14: 12.

Wood, E.M. 1953. A century of American fish culture, 1853-1953. The Progressive Fish Culturist 15(4): 147-160.