Do Hatchery Salmon Affect the North Pacific Ocean Ecosystem?

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Releases of hatchery-reared anadromous salmon into the North Pacific Ocean are currently estimated between 5 and 6 billion juveniles per year. Wild spawning salmon may produce an additional 4 to 5 times this number of juveniles. With as many as 25 billion juvenile Pacific salmon annually entering the ocean and currently producing over 1. 0 million mt of returning adults, salmon survival and production in the North Pacific Ocean is currently at historically high levels in spite of depressed runs and endangered stocks in some regions. Biological changes in size and age at maturity of some stocks have raised questions on the density effects of high abundance, and on the long-term well being and health of salmon stocks. Changes in size and age notwithstanding, favorable ocean conditions for survival and growth, even growth at reduced levels, have produced historic numbers and biomass of salmon suggesting the evidence for limitations in the carrying capacity for these fishes is inconclusive. Important studies are underway in several countries to better understand the effects of hatchery-wild stock interactions on the spawning grounds but little attention has been directed toward this issue in the ocean. New mass marking and identification technologies for both hatchery and wild fish provide mechanisms for investigating the interactions of salmon in the open ocean. Given biological concerns about ocean carrying capacity and socio-economic issues associated with record runs, should NPAFC member countries consider cooperative quotas to limit production of salmon around the North Pacific Rim? If implemented, each country could determine what portion of its quota would be derived from wild and hatchery production.

INTRODUCTION

North Pacific Rim countries with significant runs of anadromous salmon utilize hatcheries or other types of enhancement for some portion of current stock abundance. The portion of salmon abundance dependant on hatchery production, however, varies considerably among countries and across regions within countries. Although the present level of salmon abundance is at or near historic highs, some regions still have depressed runs of specific stocks. For example, both Alaska and Japan recorded all time record commercial harvest of salmon in 1995 reaching 477 and 246 thousand metric tons (mt) respectively in those regions. Preliminary estimates indicate capture fisheries for salmon throughout the Pacific Rim in 1995, not including sport fisheries, exceeded one million mt, probably an all time record. At the same time the depressed status of some stocks in Pacific Northwest states of Washington, Oregon, Idaho, and California has necessitated additional listings under the Endangered Species Act (ESA) of the United States.

Concomitant with record-level runs of adult salmon are record releases of juveniles from hatcheries. Estimates of the total numbers of juvenile salmon released from Pacific Rim hatcheries have increased from 2.6 billion in 1976 (McNeil 1979) to 4.4 billion in 1985 (McNeil 1988) to 5.5 billion in 1992 (Heard 1995). Much of the recent increase has occurred in Alaska where releases have grown from 6 million juveniles in 1976 to 1. 3 billion in 1992 (Table 1). Zorpette (1995) suggested the number of juvenile salmon entering the ocean from wild spawners each year is perhaps 20 billion individuals.

With roughly 25 billion juvenile salmon entering the North Pacific Ocean each year, production of adults originating from wild spawning parents and hatchery programs varies greatly among regions. In the United States for example, the principal source of salmon caught in capture fisheries is in Alaska. Hatchery fish have accounted for 16-30 percent of the Alaskan harvest in recent years (Heard 1996). Within Alaska, however, hatcheries make no contribution to fisheries in some areas (Bristol Bay) and over 70 percent in others (Prince William Sound). Contributions from hatcheries now account for over half of the salmon produced in the Pacific Northwest (NRCC 1996). Production from hatcheries comprises almost all of the salmon caught in Japan and in Russia hatcheries are major contributors to salmon production in the Sakhalin-Kurile Islands region.

Table 1. Estimates for numbers of juvenile salmon released into the North Pacific Ocean and adjacent seas in 1992 by hatcheries, enhancement and ocean ranching programs, in millions of fish (from Heard 1995).

Country/Region	Pink	Chum	Sockeye	Coho	Chinook	Masu	Totals
	Species						
Canada[1]	64.7	200.4	286.3	23.5	58.8	---	633.7
China[2]	---	1.0	---	---	---	---	1.0
Japan[3]							
Hokkaido	140.8	1,053.9	2.9	---	---	13.5	1,211.1
Honshu	---	987.7	---	---	---	3.4	991.1
Korea[2]	---	10.0	---	---	---	---	10.0
Russia[4]							
Sakhalin/Kuriles	584.5	206.8	---	---	---	---	791.3
Other	11.7	67.7	0.2	0.1	0.1	---	79.8
United States							
Alaska[5]	802.8	436.4	75.3	20.7	10.9	---	1,346.1
Other[6]	2.4	66.1	0.2	112.5	267.0	---	448.2
Totals	1,606.9	3,030.0	364.9	156.8	336.8	16.9	5,512.3

[1] Data from E.A. Perry, SEP, Canada DFO.
[2] Data from China and Korea provided by H. Kawamura, Hokkaido Fish Hatchery.
[3] NPAFC DOC. 40.
[4] Data from F. Rukhlov, Sakhalin Branch, TINRO.
[5] Data from NPAFC, Doc. 33; W.R. Heard, NMFS; S. Leask, Metlakatla Indian Community.
[6] Data from K. Johnson, PSMFC; I. Blanketship, WDF&W; C. Corrarino, ODF&W; and F. Fisher, CDFG.

ABUNDANCE-RELATED BIOLOGICAL ISSUES

During the past 15-20 years record levels of salmon production throughout much of the Pacific Rim have occurred simultaneously with significant biological changes in many stocks. Decline in average size of returning adults and increase in average age at maturity for some stocks pose important questions about relationships between levels of abundance, climatic factors, and capacity of the North Pacific Ocean to produce salmon (Ishida et al. 1993; Rogers and Ruggerone 1993; Kaeriyama 1996; Bigler et al. 1996). Paramount among these questions is the extent to which recent record levels of hatchery production may have influenced these biological changes.

There is no doubt that ocean survivals for many stocks of Pacific Rim salmon have been high in recent years. One can surmise, therefore, given the high levels of juveniles entering the ocean, both from hatchery and wild stocks, that survival is not negatively correlated with abundance, at least under current conditions. Favorable oceanographic and climatic factors throughout much of the Pacific Rim marine environment are likely responsible for current high survivals (Brodeur and Ware 1992; Beamish and Bouillon 1993; Klyashtorin and Smirnov 1995) irrespective of the numbers of salmon in the ocean.

Density-dependent effects of decreased size and increased age at maturity in certain salmon stocks may be associated with specific time-area phenomena. Rogers and Ruggerone (1993) suggested carrying capacity limitations for Bristol Bay sockeye salmon may be... "on migratory routes of returning adults when the fish are most concentrated and their growth most limited by their food supply". Ishida et al. (1993) found that, after 1970, significant decreases in body weight, scale radius, and width of the third-year growth zones of scales occurred in age 4 Japanese and Russian chum salmon. They attributed the cause to increasing abundance of Japanese stocks and to overlapping ocean distribution patterns of immature chum salmon from the two countries. While evidence of density-dependent effects on growth of many salmon stocks during some portion of their life history at sea seems unequivocal, there is little cogent evidence of density-dependent marine mortality or that any reduction in overall production of salmon has occurred under recent oceanographic conditions.

HATCHERY-WILD STOCK INTERACTIONS

Many recent conferences, symposia, and workshops have addressed the issue of hatchery-wild stock interactions in salmonids. Most of this attention has been directed at interactions in freshwater spawning and rearing habitats or on harvest management strategies in coastal or riverine fisheries. Biological concerns in freshwater include potential adverse impacts on wild stocks through genetic interactions including loss of diversity and fitness through interbreeding with domesticated hatchery fish (Waples et al. 1990; Hinder et al. 1991; Waples 1991). Other concerns involve depletion of wild stock spawners through egg collections for hatcheries, or over harvesting weak wild stocks in fisheries targeted on more abundant hatchery fish (Walters 1988; Hilborn 1992).

These and other related issues have spawned a plethora of continuing, sometimes heated, discussions in North America over the pros and cons of Pacific salmon hatcheries and of the future role of hatcheries in salmon management (Hilborn and Winton 1993; Winton and Hilborn 1994; Thomas and Mathisen 1993; Martin et al. 1992; Daley 1993; Incerpi 1996). Although habitat losses due to human activities in the Pacific Northwest have been major contributors to the extinction, threatened, or endangered status of many salmon runs in that region, the past extensive use and management practices of hatcheries is now thought also to have had serious adverse effects on natural populations (NRCC 1996).

Only recently have hatchery-wild stock concerns been expanded to include the ocean environment. While there are many issues associated with these concerns they, at least partly, are reflected in the following question. Do large numbers of hatchery salmon influence the ecology of the North Pacific Ocean; specifically do hatcheries affect the carrying capacity of the ocean environment to produce salmon?

Using a simple carrying capacity simulation model and assuming that salmon out-compete other potential predators for their prey, Honkalehto (1984) estimated that Pacific salmon...." consume less than 0.5% of the available zooplankton biomass and less than 5.0% of the available larval fish biomass". In another study also using an ecosystem simulation model, Favorite and Laevastu (1979) postulated the apparent North Pacific Ocean carrying capacity..... "in respect to salmon can easily sustain ten times higher standing stock of salmon than at present (provided that salmon is very competitive for food and predation on salmon is not a limiting factor)".

It has been suggested (Bigler et al. 1996) that expansion of Pacific Rim enhancement programs in the 1980s and early 1990s is a probable factor in the ocean-wide reduced size of salmon. These authors also argue the inverse relationship between the current high abundance and reduced size of salmon indicates there is a limitation to the salmon-sustaining resources of the ocean. There are ultimate limitations for any biological ecosystem, however, it can also be argued, given current record levels of abundance, that recent oceanic conditions around the Pacific Rim have provided very favorable resources for sustaining salmon. Reduced size notwithstanding, favorable ocean conditions for survival and growth, even growth at reduced levels, have produced record historic levels of salmon abundance and biomass. Pearcy (1992) felt that growth rates were more sensitive than survival rates and that growth would provide the best evidence for density dependence. He found, however, that evidence was inconclusive for limitations in the carrying capacity of salmonids in the North Pacific.

Beamish and Bouillon (1993) concluded that recent trends in salmon abundance were not primarily a result of fishing effort, management actions, or artificial rearing, but rather were strongly linked to climatic factors and a favorable ocean environment. In another report Beamish (1993) found that sudden physical changes in marine environments dramatically affects population dynamics of many fishes, almost simultaneously over vast ocean areas. Density-dependent effects resulting in reduced size may reflect limited time-area food or space resource bottlenecks along ocean migration pathways. Overall survival, however, may be more reflective of the integrated, collective influences of marine environments for salmon production. It seems, therefore, that a concept of ocean carrying capacity for salmon (or any other group of organisms) is not a fixed or static situation and precice definitions are difficult, even evasive. Ocean carrying capacity is a highly dynamic ecosystem principle that fluctuates often, perhaps in a cyclic manner, and is strongly influenced by a plethora of ecological variables, and, generally, is poorly understood.

OCEAN TRACKING HATCHERY-ORIGIN AND WILD-ORIGIN SALMON

Recent developments in stock identification and in mass marking technologies provide avenues for examining interactions of hatchery and wild salmon in the open ocean environment. Coded wire tags (cwt) are used extensively in North America for research and management of both hatchery and wild salmon. This technology, used principally on chinook and coho salmon, requires placing tags in individual fish and is more widely used on hatchery fish than on wild fish. Nevertheless, around 40 million cwt marked juvenile salmon are released into the ocean each year (Johnson and Longwill 1993) and this technology has provided much of the knowledge currently used in scientific management of many coast wide stocks and fisheries.

The use of controlled thermal events in hatcheries allows development of specific recognizable banding patterns on otolith structures of embryonic salmonids (Volk et al. 1990; Schroder et al. 1996). Banding patterns developed on embryos remain identifiable throughout subsequent life stages. This technology is developing rapidly and now provides the potential to use bar code symbology to identify point sources, and even differential treatments within groups of fish from the same hatchery. Fishery science now has the ability to otolith mark every hatchery salmon released into the North Pacific Ocean (Volk et al. 1994). Otolith marks on hatchery-origin salmon are now used as a real-time decision tool for management of some North American commercial fisheries and in monitoring homing and straying patterns of hatchery fish.

In 1996 the estimated number of otolith marked salmon released from North American hatcheries was 870 million fish (Table 2). Expanding otolith thermal banding to other North American and to Asian hatcheries, perhaps with some form of an oversight role by North Pacific Anadromous Fish Commission (NPAFC), would provide a powerful research potential to more fully understand distribution, migration and behavior patterns, throughout the Pacific Rim, of hatchery-origin salmon in the ocean environment. Some recent projects examining otolith patterns of ocean-caught juvenile and immature salmon, including those caught as unintended bycatch in non-salmon fisheries, are just beginning to realize some of this potential (Ignell et al. 1997) .

Wild stocks of salmon can be identified in the ocean at differing levels of resolution with a variety of procedures including scale pattern analyses (Major et al. 1978; Myers et al. 1987), genetic stock identification (gsi) techniques (Beacham et al. 1987; Utter 1989; Wilmot et al. 1992), parasite markers (Margolis 1963; Urawa et al. in press), and applications of DNA technology (Park et al. 1994). Species-wide protein electrophoreses baselines now provide a basis for estimating the regional origins of complex mixtures of salmon sampled in the open ocean (Winans et al. in press; Hawkins et al. in press).

Another procedure for identifying wild stocks of salmon in the open ocean involves spectrographic analysis of trace elements found in the composition of primal bone structures. The procedure, laser ablation inductively coupled plasma mass spectroscopy (LA-ICPMS), analyzes micro vaporized portions of otolith or scale nuclei to detect differences in elemental composition that reflects uniqueness of the hydro geochemistry of natal waters. Using discriminant function analysis this concept has been successfully used to identify separate stocks of steelhead trout (*O. mykiss*) in the Skeena River watershed of British Columbia (Robert Brown, Elemental Research Inc., personal communication) and Atlantic cod (*Gadus morhua*) from different spawning grounds in the northwest Atlantic (Campana et al. 1994).

The idea of an elemental fingerprint within the scale nucleus of individual stocks of salmon is an exciting concept that should be closely examined as a tool to identify wild stocks in the ocean. This principle likely holds the most promise for species with sufficient residence time to firmly establish a fingerprint in freshwater habitats. Furthermore, extensive scale collections by researchers around the Pacific Rim could provide a readily available database for many stocks.

DISCUSSION

There are many unanswered questions about salmon ecology in the North Pacific Ocean (Pearcy 1992), and more specifically about how hatchery and wild fish may or may not interact in the marine environment. Are ocean distribution patterns similar for wild and hatchery salmon from the same region or river system? When young fish leave riverine and near shore coastal regions, do wild and hatchery salmon from the same areas mingle together or remain in relatively discrete groups? Are there differences in dietary preferences of the two groups? Specific answers to these and other similar questions are limited, hence a definitive answer to the question title of this paper, "Do hatchery salmon affect the North Pacific Ocean ecosystem?" is equivocal.

With few exceptions there is lack of cogent evidence that hatchery salmon have any direct affect on the North Pacific Ocean ecosystem. One exception noted by Ogura and Ito (1994) documented a change in the known ocean distribution of chum salmon. These authors concluded an enlargement in ocean distribution of Japanese chum salmon was associated with dramatic increases in numbers of chum salmon produced by Japanese hatcheries. Ocean research in other regions should determine if large hatchery releases of juvenile salmon are also affecting ocean migration and distribution patterns. Increased otolith marking of hatchery juveniles and expanded use of available tools for identifying wild stocks, coordinated with an effective ocean sampling program, can provide new insight into these and related issues.

Table 2. Estimated number of otolith marked juvenile salmon released from North American hatcheries in 1996 (in millions).

Area	Species					
	Pink	Chum	Sockeye	Chinook	Coho	Total
Washington	----	----	9.0	13.0	----	22.0
British Columbia	----	18.0	----	22.0	----	40.0
Alaska						
Southeast	9.0	146.0	4.1	0.6	1.0	160.7
Prince William Sound	645.0	----	----	----	----	645.0
Cook Inlet	----	----	2.7	----	----	2.7
Totals	654.0	164.0	15.8	35.6	1.0	870.4

Based on the current high survival rates of wild and hatchery fish reflected in record runs in many Asian and North American stocks, there is little evidence the overall carrying capacity of the North Pacific Ocean for salmon production has been exceeded or diminished. Helle (1989) found a strong positive correlation between body size of chum salmon spawners at Olsen Creek, Alaska and subsequent life history survival of their progeny (cumulative survival for freshwater, marine, and coastal fishery periods). It follows, given this parent progeny relationship and the density-dependent effects of decreased body size in many stocks, that present survival rates should be diminishing or trending downward. In general, however, this has not happened and overall cumulative survivals are currently at record high levels.

Although strong evidence is lacking for limitations in ocean carrying capacity, record runs of Pacific salmon both in Asia and North America have severely depressed prices paid to fishermen (Kaeriyama and Urawa 1993; Heard 1996). In some instances surplus runs of salmon have gone unharvested due to lack of price or demand. Continued world-wide growth of farmed salmon also directly affects both price and demand of anadromous species. The current levels of salmon abundance have created socio-economic concerns over the long-term status and well being of capture fisheries in many areas. Given these concerns along with the many biological questions about carrying capacity of the North Pacific Ocean, perhaps NPAFC member countries should consider a concept of cooperative quotas or a partitioning system to limit production of Pacific Rim salmon. Such a system could allow each country to decide what portion of its quota would be derived from wild and hatchery fish.

The idea of a quota or partitioning of Pacific salmon production among countries is not new. Joyner (1975) outlined a system of using the seas as a range or cropland including a concept of North Pacific Ocean grazing rights for salmon production. Bigler et al. (1996) suggested that allocation of ocean resources may need to be considered for.... "optimal common management of salmon".

In terms of current hatchery programs, Japan has had a self-imposed quota or cap on the number of juvenile chum salmon released from hatcheries for over a decade. Since about 1982 the numbers of juvenile salmon released in Japan has been fixed at about 2 billion fry per year (Kaeriyama 1989; Kaeriyama and Urawa 1993). Japanese fry releases of chum salmon during this period have been divided about equally between Hokkaido and Honshu. Dramatic increases in numbers of adult chum salmon produced from Japanese hatcheries have been solely the result of continued increases in ocean survival unrelated to any increased output of hatchery fry.

Variability in marine survival clearly illustrates only one of the many issues that would need to be addressed in a Pacific Rim quota system for limiting or allocating production. Predicting survival by brood year of either wild or hatchery salmon would become a key element in any quota program. In turn this would require a more comprehensive understanding of the dynamics of ocean ecology and the role of salmon in the North Pacific Ocean ecosystem.

Even without a cooperative effort toward a concept of quotas, understanding interannual variations in ocean survival of salmon is a worthy goal. The issue of survival along with many other aspects of marine ecology of salmon, including better knowledge of hatchery-wild stock interactions, is sufficient reason to continue and expand joint oceanic research by NPAFC member countries around the Pacific Rim.

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