A Coordinated Research Plan for Estuarine and Ocean Research on Pacific Salmon

By Richard D. Brodeur, George W. Boehlert, Ed Casillas, Maxwell B. Eldridge, John H. Helle, William T. Peterson, William R. Heard, Steven T. Lindley, and Michael H. Schiewe

ABSTRACT

The National Marine Fisheries Service (NMFS) is charged with restoring and protecting anadromous Pacific salmon stocks in all habitats of U.S. waters, including their period of residence in estuarine and oceanic waters. Recent studies have implicated the estuarine and coastal phase of the salmon life cycle as being of equal importance to the freshwater phase in determining production. Evaluation of the freshwater phase of salmon has yielded a better understanding of the factors limiting production in this environment; however, a comparable understanding in the marine environment is lacking. Currently, some marine salmon research is being conducted at various NMFS labs on the West Coast, but there has been little attempt to coordinate activities among the different regions. In response, we propose a comprehensive plan to address ocean and estuarine survival of salmon by identifying research needs and suggesting ways to meet these needs. We recommend that NMFS research focus on (1) distribution and movement patterns of salmon in marine waters, (2) health and condition of hatchery and wild salmon, (3) trophic dynamics of salmon, and (4) large-scale effects of the atmosphere and ocean.

Introduction

Anadromous Pacific salmon (*Oncorhynchus* spp.) have been an integral part of the culture and livelihood of the North Pacific long before and ever since European and American settlement (see Yoshiyama et al. 1998). Commercial, subsistence, and recreational fisheries for salmon have provided enormous economic benefits to North America, in addition to providing important sources of protein for a growing human population. Recently, production of wild salmon has been declining along the West Coast, stemming directly from the fisheries and indirectly from the effects of pollution, habitat loss, water diversion, and damming of traditional spawning rivers (National Research Council 1996). These impacts have led to the establishment of an extensive hatchery production system that for some species far exceeds the wild production (Heard 1998; Mahnken et al. 1998). Artificial enhancement has not held up to expectations in the Pacific Northwest and indeed may have led to unintended negative consequences (Walters 1988; Hilborn 1992; Meffe 1992). In recent years, despite continued high levels of artificial propagation, returns of salmon in many rivers have continued to decline, leading to listings of several wild salmonid populations as threatened or endangered under the federal Endangered Species Act (ESA). In fact, some populations in the Pacific Northwest have been declared extinct (Nehlsen et al. 1991; Kope and Wainwright 1998).

Conversely, at a time when many populations of Pacific Northwest salmonids have approached all-time lows, other northern populations—including both wild and hatchery stocks—originating in Alaska have had record-high runs. Indeed, West Coast and Alaska stocks have varied inversely with each other for some time (Mantua et al. 1997; Hare et al. 1999). Moreover, stocks in many adjacent river systems with highly varying morphology and hydrology show similar production trends, which suggests some large-scale regional process or processes affect these stocks. Although climatological factors such as precipitation affect freshwater systems as well as salmon survival, scientists believe that ocean conditions contribute to interannual variability in salmon survival and growth (Pearcy 1992), particularly in the first few months after leaving freshwater. Large-scale climatic factors affect ocean productivity and thus carrying capacity for salmonids (Pearcy 1996; Beamish et al. 1997; Cooney and Brodeur 1998).

Despite increased awareness and several attempts at synthesizing the major marine effects on salmonid

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Richard D. Brodeur *is a research fishery biologist and* ***William T. Peterson*** *is an oceanographer at the Northwest Fisheries Science Center, Newport, OR 97365; Rick.Brodeur@noaa.gov. Brodeur worked on this article while employed by the Alaska Fisheries Science Center, Seattle, WA 98195.* ***George W. Boehlert*** *is an oceanographer at the Southwest Fisheries Science Center, Pacific Grove, CA 93950.* ***Ed Casillas*** *and* ***Michael H. Schiewe*** *are research fishery biologists at the Northwest Fisheries Science Center, Seattle, WA 98112.* ***Maxwell B. Eldridge*** *is a research fishery biologist and* ***Steven T. Lindley*** *is an ecologist at the Southwest Fisheries Science Center, Tiburon, CA 94920.* ***John H. Helle*** *and* ***William R. Heard*** *are research fishery biologists at the Alaska Fisheries Science Center, Auke Bay, AK 99801.*

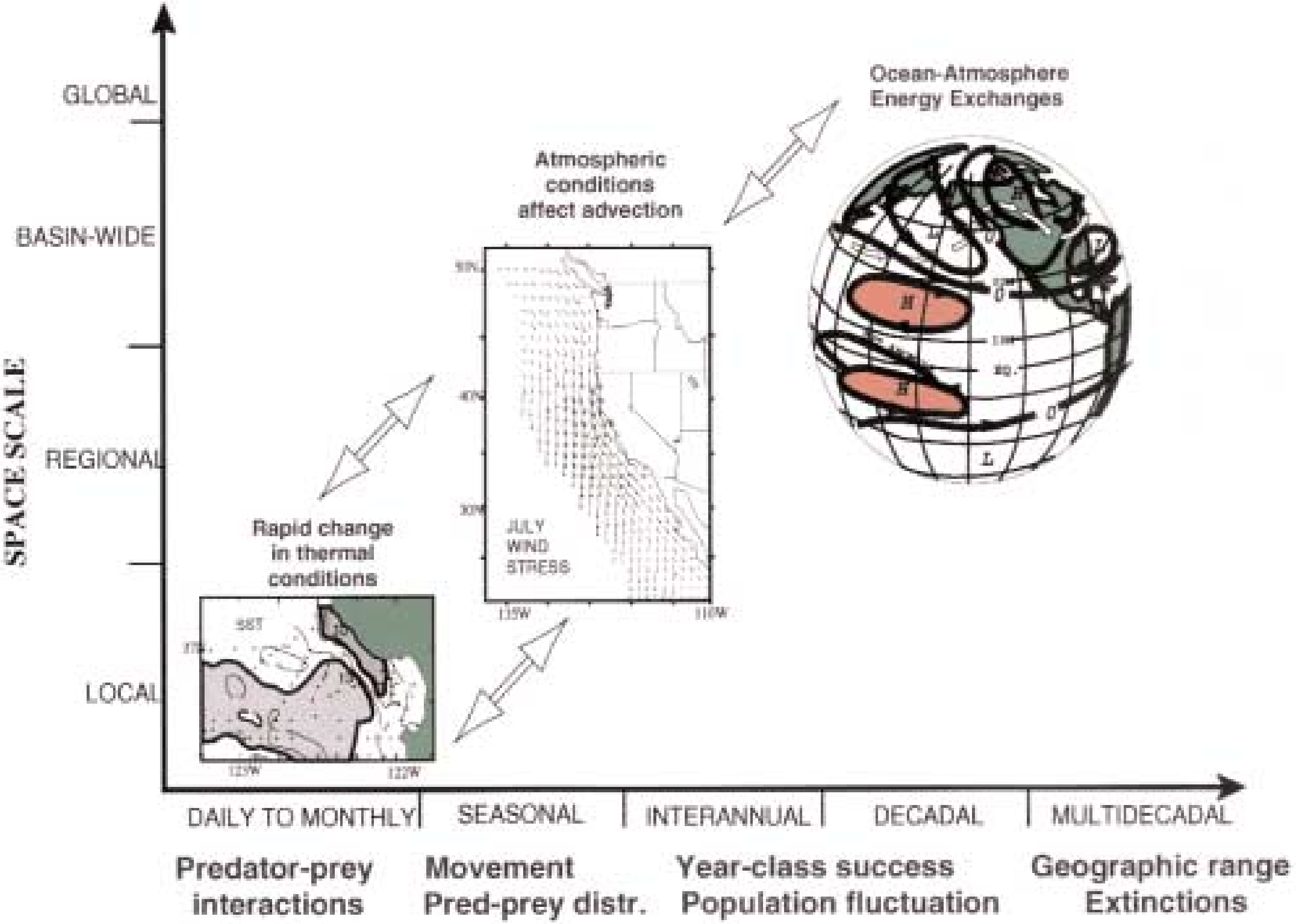

Figure 1. Spatial and temporal scales of physical variability affecting marine fish populations are shown. The inset figures give examples of the kinds of environmental variability operating at these scales, and the effects listed at the bottom are indicative of how this variability operates on salmon populations.

growth and survival (Pearcy 1984, 1992; Emmett and Schiewe 1997), we still have a rather poor understanding of the ecology of salmon once they leave their natal rivers. Much effort in evaluating the freshwater phase of salmon has yielded a better understanding of the factors limiting production in that environment. However, we lack a comparable understanding of the marine environment, despite evidence that this habitat contributes as much, if not more, to population variability than the freshwater environment (Bradford 1995, 1997). The estuarine, coastal, and open-ocean environments continue to function as “black boxes,” into which salmon juveniles enter and from which some small but variable percentage later return as adults. An incomplete understanding about the basic aspects of salmon biology in marine waters has hampered our ability to predict natural variability in salmon production, with important management and economic ramifications.

As stewards of the nation’s marine and some anadromous fish populations, the National Marine Fisheries Service (NMFS) is responsible for protecting and rebuilding threatened and depleted stocks and for maintaining healthy stocks. Substantial resources have been dedicated to understanding and improving freshwater survival, but little effort has been directed toward understanding variability in salmon survival during estuarine and ocean residence. Several NMFS laboratories along the West Coast have independent marine research projects dealing with salmon in marine waters (Table 1). However, NMFS does not have a comprehensive plan under which it can organize its activities and develop mutually beneficial and synergistic research programs with universities, state agencies, and other government laboratories. A coordinated research plan is needed to maximize efficiency of the NMFS research effort and to facilitate cooperative work with research and management entities. In this article, we review past and existing NMFS and extramural marine research programs on salmon and suggest research priorities and approaches.

Background

NMFS has supported some estuarine, coastal, and open ocean research on salmon for many decades. Some of this support has been in the form of grants or contracts to academic institutions. Examples are the long-term High Seas Research Program (Burgner 1992; Myers et al. 1996, 1997) and the coastal salmon study (Hartt and Dell 1986) of the Fisheries Research Institute at the University of Washington, and the multi-year early marine life history of salmon research conducted by Oregon State University in the 1980s (Pearcy et al. 1989; Pearcy and Fisher 1990; Fisher and Pearcy 1990). In addition, the National Oceanic and Atmospheric Administration (NOAA), the parent organization of NMFS, supports some West Coast salmon research under the auspices of its Coastal Ocean Program, through interdisciplinary programs such as Global Ocean Ecosystem Dynamics (GLOBEC) and Pacific Northwest Coastal Ecosystem Region Study (PNCERS).

Historically, the Bureau of Commercial Fisheries, the predecessor of NMFS, was directly involved with high-seas salmon research as part of the U.S. contribution to the International North Pacific Fisheries Commission (INPFC). This international body generated useful information on the life history, distribution, and ecology of maturing salmon, much of it published in the INPFC Bulletin Series. As a result of these investigations, researchers developed some of the earliest descriptions of the oceanography of the North Pacific (Favorite et al. 1976), which led to initial attempts to estimate the ocean carrying capacity for salmon (Favorite and Laevastu 1979). A new international organization, the North Pacific Anadromous Fish Commission (NPAFC), replaced the INPFC, with a renewed focus on cooperative marine research on salmonids among four Pacific Rim nations (Canada, Japan, Russia, and the United States).

By the 1970s and 1980s, the main focus of NMFS marine salmon research had shifted away from the open ocean to concentrate on estuarine and coastal waters. The Northwest Fisheries Science Center has conducted extensive salmonid research at the mouth of the Columbia River and in the nearshore coastal region (McCabe et al. 1983; Miller et al. 1983; Dawley et al. 1985). The Northwest Center also led efforts to refine techniques to determine sources and migration patterns of salmon in coastal waters and in the open ocean using genetic stock identification (Winans et al. 1994, 1998), and to develop criteria to identify distinct population segments of salmon (Waples 1991). Such work allowed the development of much-needed status reviews of West Coast salmonids (e.g., Weitkamp et al. 1995). The Alaska Fisheries Science Center's Auke Bay Laboratory has long conducted research on the nearshore habitat utilization and ecology of salmonids in both the Bering Sea (Straty 1974) and the inside and coastal waters of southeast Alaska (Jaenicke and Celewycz 1994; Orsi and Jaenicke 1996; Landingham et al. 1998). Despite their emphasis on nearshore and coastal waters, the Auke Bay Laboratory also continued to study high-seas salmonids after the termination of large-scale pelagic driftnet fisheries in the 1990s (Dahlberg et al. 1992).

Concurrent with these studies, NMFS scientists in Alaska have been monitoring the age and size at maturity of chum salmon since 1959. During the past 20 years, body size has decreased, and the age at maturity has increased in many stocks of salmon in both North America and Asia (Helle and Hoffman 1995, 1998; Bigler et al. 1996). These changes are associated with large increases in salmonid production that coincide with major changes in ocean climate in the North Pacific Ocean that began in about 1976. The inverse relation between body size and abundance of salmon in the ocean suggests that there may be limits to the carrying capacity of the North Pacific Ocean for salmonid production. In response to this evidence, the NPAFC called for research on the "critical issue of the impact of change in the productivity of the North Pacific Ocean on Pacific salmon" by studying factors affecting (1) current trends in ocean productivity and their effects on salmonid carrying capacity, and (2) changes in the growth, size at maturity, oceanic distribution, survival, and abundance of Pacific salmon. The Ocean Carrying Capacity Program (OCC) at Auke Bay Laboratory was formed in 1995 to address these NPAFC concerns.

Many current or planned research projects aimed at understanding salmon survival in estuaries and coastal ocean areas are being undertaken at the various NMFS laboratories on the West Coast (Table 1). The different centers' priorities are partly based on the available expertise at each laboratory, but more importantly reflect the different species

Table 1. Ongoing or planned salmon-related estuarine and ocean research at the various National Marine Fisheries Service West Coast laboratories are listed. Also shown is a listing of our recommended priorities being addressed by each of these studies.

Center	Laboratory	Project	Initiation	Principal investigators	Priorities addressed
Alaska Center	Auke Bay	Ocean carrying capacity	1995	Helle, Ignell, Carlson	1, 3, 4
Alaska Center	Auke Bay	Early ocean salmon	1985	Heard, Wertheimer, Orsi	1, 3
Alaska Center	Auke Bay	Salmon genetics	1985	Wilmot, Kondzela, Guthrie	1, 2
Northwest Center	Seattle/Newport	Salmon health	1995	Stein, Arkoosh, Casillas, Jacobson	2
Northwest Center	Seattle	Conservation biology	1970	Waples, Hard, Grant, Weitkamp	1, 2, 4
Northwest Center	Newport/Seattle	Estuarine ecology	1970	Schiewe, Casillas, Bottom	1, 2, 3
Northwest Center	Newport/Seattle	Ocean ecology	1997	Peterson, Brodeur, Emmett, Casillas	1, 2, 3, 4
Northwest Center	Seattle/Newport	Population modeling	1997	Kope, Lawson, Wainwright	2, 4
Southwest Center	Tiburon/Santa Cruz	Population modeling	1997	Mohr, Goldwasser, Lindley, Bjorkstedt	2, 4
Southwest Center	Tiburon/Santa Cruz	Ecology and genetics	1997	Eldridge, MacFarlane, Garza	1, 2, 3
Southwest Center	Tiburon/Santa Cruz	Estuarine ecology	1998	Adams, Williams	1, 2, 3
Southwest Center	Pacific Grove	Ocean variability	1995	Boehlert, Schwing, Parrish	1, 4

Table 2. Research capabilities and activities of the National Marine Fisheries Service laboratories on the West Coast in estuarine (E), coastal (C), and oceanic (O) waters.

	NWC			SWC		AKC
Research area	Seattle	Manchester	Newport/ Pt. Adams	Tiburon/ Santa Cruz	Pacific Grove	Auke Bay
Distribution			E, C, O	E, C	C, O	E, C, O
Trophic ecology			E, C, O	E, C		E, C, O
Predation	E, C		E, C	E, C		E, C
Habitat utilization			E, C	E, C		E, C, O
Carrying capacity			C, O			E, C, O
Fish health			E, C	E, C		
Genetics	C, O			E, C		E, C, O
Population modeling	E, C		E, C	E, C		E, C
Ocean variability					C, O	
Tagging and migration	E		E	E	C, O	E, C, O
Archival tagging	E, C	E, C	E, C	C		E, C, O
Physiological ecology	E, C	E, C	E, C	E, C		E
Gear and sampling			E, C	E, C		E, C, O
Laboratory research	E, C	E, C	E, C	E, C		E, C

and systems found in each region. The Alaska Region contains more “natural” freshwater and estuarine systems, high current production levels, and a relatively high percentage of naturally produced fish. Therefore, its management and research goals fall under the NOAA initiative to “Build Sustainable Fisheries.” In contrast, the Northwest and Southwest regions operate in settings where freshwater and estuarine systems have been heavily affected by human activities (e.g., water usage, forestry and agricultural practices, dredging, urban development). In addition, abundance is currently low for the most part and hatcheries play a major role in salmon production in many river systems. The driving force for many research and management needs is to protect and promote the recovery of stocks that remain. Such objectives fall within the “Recover Protected Species” element in NOAA’s strategic plan.

Despite this regional dichotomy, some commonality exists in the needs for research on estuarine and marine survival. The diversity of salmon species, geographic ranges, life history, and habitat utilization patterns (Kope and Wainwright 1998) requires a broad-based approach to address many of these data gaps. The estuarine and early ocean habitats occupied by salmon vary from the broad shallow shelf and relatively stable waters of the Bering Sea to the narrow shelf and highly dynamic waters off northern California. Moreover, juvenile salmon enter into protected waters in Puget Sound, Prince William Sound, and southeast Alaska, whereas they directly enter the ocean from most other areas. Thus it would be unwise to extrapolate findings from one major region to another even for the same species. However, we feel that comparing these divergent river and coastal systems, species, and life history patterns will make advances in our understanding of production dynamics of salmon.

Approach

The estuarine and ocean environments in the North Pacific respond to forcing on a number of different spatial and temporal scales (Ware 1995). Salmon populations respond to many of these, varying from large-scale climatic oscillations (Francis and Hare 1994; Mantua et al. 1997) to meso-scale and smaller-scale effects (Brodeur 1997). Therefore, we contend that to achieve even a minimal understanding of ocean effects on salmon, we must pursue a multifaceted approach that examines many of the relevant spatio-temporal scales concurrently (Figure 1) and that draws upon the expertise available in NMFS (Table 2). Success also will depend on using new technologies and analytical methods presently being developed in fisheries and other sciences. The overall goal of this plan is to understand the causes of variability in salmon production (e.g., survival, growth, and age of maturity) in the North Pacific attributable to the parts of the life cycle spent in estuarine, coastal, and open ocean waters. In particular, we believe it is important to partition mortality among these three marine habitats to better understand limitations to salmon production.

We developed a list of research elements that address the needs of management and that we believe the NMFS should implement in the coming decade. Our list is extensive but not exhaustive, and we omitted possible research avenues that may be better pursued by academic institutions, given our limitations in funding. We prioritized our elements based on our present knowledge gaps and where we can make the greatest gains in understanding. To achieve this goal, NMFS should focus on the following objectives in order of priority:

(1) *Understanding distribution and movement patterns of salmon in the ocean*—Despite the research described previously, we still have an incomplete understanding of distribution and ecology of juvenile salmon in nearshore and coastal environments. Some areas of early marine distribution (e.g., northern California, Alaska Peninsula, and Bering Sea) have been poorly sampled, and we have little information on the water masses occupied by salmon or seasonal salmon movement patterns. Even in better sampled regions (i.e., Oregon, Washington, British Columbia, southeast Alas-

ka, and Gulf of Alaska), we know little about small-scale diel movement patterns, residence times, and habitat preferences of salmon once they enter salt water. This information, which is a critical input to Individual Based Models (Rand et al. 1997) or life history models (Mangel 1994), can only be attained by systematic sampling for several years, especially during the first few months that salmon spend at sea. Similarly, we lack information on the oceanic distribution and habitat utilization of adult salmonids, especially during the winter, which may be a critical period in their existence.

Although general information about where a species is found at what time is useful, detailed stock-specific information is necessary to protect endangered stocks. Recent findings (McKinnell et al. 1997) that salmonids from the same populations may aggregate together years after ocean entry provide tantalizing evidence of stock-specific migration patterns. Continued analysis of coded-wire tagging data (Myers et al. 1996) and increased use of genetic markers (Winans et al. 1994, 1998) and archival tags (Boehlert 1997) will fill gaps in our knowledge of the oceanic distributions of most salmon stocks.

Given the low abundance of some at-risk populations, preference should be given in these cases to noninvasive and nonlethal techniques that provide as much information as possible while sacrificing few, if any, fish. For example, using new technologies such as archival, passive integrated tags (PIT) and acoustic tags mounted on individual fish (Boehlert 1997; Walker et al. 2000) and remote sensing using LIDAR (LIght Detection and Ranging) (Gauldie et al. 1996) can lead to rapid advances in the knowledge of distribution and abundance patterns. Application of acoustic side-scan sonars, widely used in nonsalmonid research (Misund 1997), to surface-oriented and widely dispersed salmon populations also has potential. Moored acoustical sensors in estuarine and coastal sites may enable more detailed analysis of salmon spatial organization and habitat use than is available using net sampling (Voegeli et al. 1998).

In cases where collecting salmon may provide important information, new sampling gears need to be developed to quantitatively assess the horizontal and vertical distribution of juvenile and adult salmon and simultaneously sample the abiotic and biotic environment in which they were caught or had recently traversed. Statistical comparisons and evaluations should be made of the habitat preferences of these juveniles in the estuarine and coastal environments. It may be necessary to use different sampling methods for different species and/or populations, but there should be inter-calibration of these methods so comparisons can be made among regions and across time.

(2) *Understanding the role of health and condition of hatchery and wild fish in ocean survival*—Hatchery fish do not survive as well as wild fish in estuaries and coastal ocean areas (Coronado and Hilborn 1998) and fish from different hatcheries do not have equal survival rates, suggesting that differences in the condition of released fish or in hatchery release practices vary greatly. Technology is available now to mass-mark all individuals from a particular hatchery using thermal otolith tags so their movements and survival can be followed through time (Farley and Munk 1997). New methods for mass-marking wild fish should be developed so that direct comparisons between wild and hatchery stocks can be made in estuarine and ocean environments. Histopathological comparisons of cultured and wild fish can be used to determine the prevalence of hatchery-derived diseases (e.g., bacterial kidney disease). Traditional methods of fish scale analysis should be continued, particularly for detecting density-dependent early marine growth and survival. These should be supplemented, when possible, with newer methods of detecting subtle variations in growth and condition (e.g., RNA/DNA ratios and lipid markers (Azuma et al. 1998)). Rapid, easy-to-use bioassays are needed to detect lethal and sublethal anthropogenic effects on juvenile salmon health and condition (Casillas et al. 1997; Arkoosh et al. 1998). The biochemical, pathological, and physiological properties of fish that succumb to predation should be compared to the population as a whole to determine whether predation is nonrandom.

(3) *Understanding trophic dynamics and food webs leading to and from salmon*—It is unclear whether bottom-up or top-down processes, or some combination of both, limit salmon production in estuarine and nearshore coastal environments. This is one of the most challenging areas in salmon research (e.g., Perry et al. 1998), and one that will require a concerted effort to make substantial gains. Although knowledge is accruing on freshwater and estuarine predators and competitors of juvenile salmon (McCabe et al. 1983; Fresh 1996; Emmett 1997), ecologically important taxa in coastal waters have not been adequately identified (Pearcy 1992).

Researchers study juvenile salmon in southeast Alaska with the National Oceanic and Atmospheric Administration research vessel *John N. Cobb.*

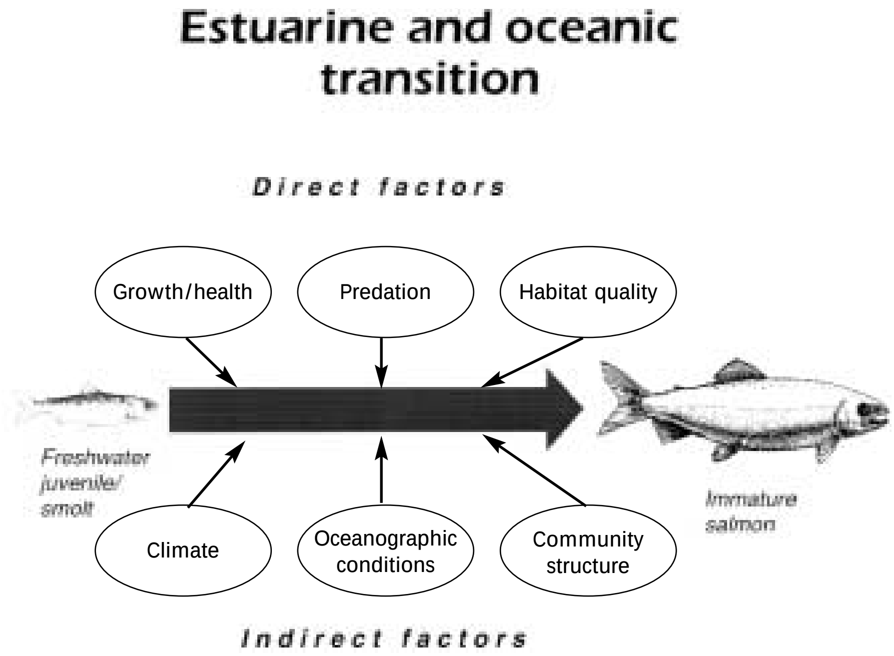

Figure 2. Diagram showing the factors related to salmon survival as they transition from freshwater to the ocean environment.

In addition, because we lack basic information on the abundance, food habits, and feeding rates of potential competitors and predators, we have been unable to assess their impacts on salmon populations. A substantial amount of information exists on what prey salmon consume in estuarine and marine waters (McCabe et al. 1983; Brodeur 1990; Landingham et al. 1998) and how their diet varies in relation to oceanographic conditions (Brodeur and Pearcy 1992). However, only a limited amount of information is available on salmon prey selectivity, feeding rates, and overall food consumption relative to available food resources (e.g., Wissmar and Simenstad 1988). Accurate estimates of food consumption and growth potential will require a combination of field and laboratory studies, thus providing useful inputs to spatially explicit bioenergetic models (Brodeur et al. 1992; Perry et al. 1996; Rand et al. 1997).

Measurement of production rates of the lower trophic levels used by salmon are also lacking and, presently such rates can be approximated only by using models. Comparisons should be made of estuarine dynamics, diet, and food consumption for the same salmon species in estuaries along a latitudinal gradient. In coastal environments, the importance of meso-scale features such as riverine plumes, eddies, and coastal jets, relative to the coastal ocean as a whole, needs to be assessed. This will require detailed comparisons of the distribution patterns and growth of juvenile salmon, their predators, and prey between these features and at reference sites. A broad array of satellite sensors is available to remotely assess and monitor salmon habitat (Boehlert and Schumacher 1997) and should be used with future field sampling.

It will be important to gather information on longer-term feeding histories and food dependencies of salmon to see how these change through time, necessitating the use of isotopic methods of analysis (Perry et al. 1996). Stable isotopes also can be useful for calibrating and/or validating food web models and can provide crude indications of ocean distribution (Welch and Parsons 1993). Long historical collections of scale samples should be analyzed for isotopic composition to see if the feeding habits of salmonids have changed in response to large-scale regime shifts. This methodology also may be effective in determining the effect of past El Niño events on the food availability and growth of juvenile and adult salmonids (Fulton and LeBrasseur 1985; Brodeur and Pearcy 1992).

(4) *Understanding how atmospheric and oceanographic processes affect salmon production and survival*—Variability in atmospheric and oceanographic processes is clearly important in the interannual and interdecadal differences observed in salmonid survival and production (Mantua et al. 1997; Beamish et al. 1995, 1997, 1999). These processes operate at several scales, but our ability to detect the dynamic relationships is hindered mainly by the dearth of appropriate biological information. Results from research in the above three priority categories will improve our ability to understand these relationships, particularly at shorter time scales, and advance our ability to make reliable fishery predictions.

Environmental data useful for fisheries research and management is readily available (Boehlert and Schumacher 1997) and their relationships to salmon survival (e.g., Kope and Botsford 1990; Mantua et al. 1997) need to be extended to include new populations and additional potential explanatory variables as more biological data become available. Relationships using only one physical variable often degenerate over time (c.f., Lawson 1997) and we need to go beyond correlations to determine how the environment affects salmon through impacts on food resources or predator distributions (Gargett 1997). The variables examined should be at the appropriate scale and affect the relevant phases of salmon life history (Brodeur 1997). Where adequate data are available, analyses of fishing patterns and production dynamics that integrate freshwater and marine influences should be made at individual stock levels (Farley and Murphy 1997).

Implementation

The attainment of many of these research objectives would be facilitated by close cooperation with various academic, state, and international entities, but we believe that NMFS would need to take a leadership role in initiating and completing this research plan. A large number of direct and indirect factors affect juvenile salmon in estuaries and the ocean (Figure 2). Addressing their relative contributions to salmon survival will demand a broad-based approach operating on many spatial and temporal scales. Following the example of many large-scale, interdisciplinary programs (e.g., GLOBEC), we suggest that a new NMFS program be organized around four intermeshed and concurrent activities: retrospective analysis, monitoring, process studies, and modeling.

Retrospective studies of climatology, biological and physical oceanography, and salmon biology at several spatio-temporal scales can provide information on what parts of estuarine and oceanic residence may be most critical to salmon and lead to formulation of hypotheses that can be addressed by other activities. The continuation of physical and biological indices presently being monitored—as well as the establishment of new "pulse points" in the system—is strongly encouraged, especially since climate and ecosystems continue to change in unpredictable and unprecedented ways. Systematic sampling of estuaries and oceans and the biota they support will provide useful information on where salmon reside and, possibly why they are there rather than elsewhere. An extension of these process studies would be controlled manipulative experiments, which can lead to rigorous testing of competing hypotheses on the importance of various factors. Data available from the above activities can be assimilated in realistic biophysical models to further examine hypotheses and management strategies under different environmental scenarios.

Conclusions

A common excuse for not expending much effort to study salmon once they leave fresh water is that the marine environment is naturally variable, and we can do little to ameliorate adverse ocean impacts. This may be true to some extent; but, in reality, humans impact the estuarine and coastal regions through global warming, introduction of exotic species, deposition of pollutants, and physical alteration of habitats through manipulation of riverine inputs, dredging, and bottom fishing. All of these may affect marine ecosystems in ways we cannot comprehend. We also may have indirectly affected salmon by creating legislation that protects species (endangered birds and marine mammals) that prey on salmon to the point that many of these species have reached historically high abundances (Stone et al. 1997). Finally, we have attempted to make up for declining natural runs by increasing hatchery production that may have compromised the estuarine and ocean carrying capacity for salmon (Cooney and Brodeur 1998), leading to density-dependent food limitation in the winter months (Pearcy et al. 1999). These anthropogenic factors may be set against a backdrop of natural variability, which may further exaggerate their effects.

Because we artificially enhance the number of salmon entering the marine environment, we have responsibility for and control over density-dependent effects in many salmon stocks. An estimated 5 billion–6 billion juvenile hatchery-reared salmon are released into the North Pacific Ocean every year (Heard 1998). Along the West Coast, hatchery production exceeds wild production in many river systems. It is essential that scientists develop better knowledge about interactions between hatchery and wild salmon in the marine environment. Only when there is greater understanding about these interactions and the ways in which wild and hatchery salmon in the estuary and ocean may differ or behave similarly in terms of feeding, migratory behavior, distribution, growth, and mortality patterns, can we have rational stock enhancement programs.

It is often suggested that we should focus our efforts on things that we can control such as restoring habitat losses in freshwater. Since we cannot control the ocean, why bother to study its influence on salmonids? Our view is that in order to measurably evaluate the success of habitat restoration programs, we must have some understanding of the degree to which ocean productivity might be changing as well, since the ocean significantly affects and can even govern productivity of salmonid stocks. We need a strong sustained research program that focuses on the effects of ocean variability on marine survival of salmonids because salmon stocks can respond clearly and suddenly to shifts in climate. It is incumbent upon oceanographers and fishery scientists to determine which physical and biological processes lead to higher (or lower) salmon growth and survival so that if (or when) the ocean enters a different climate state, and salmon growth and survival increases (or decreases), scientists will be able to state with some certainty to what degree ocean variability was responsible for this shift in growth and survival.

A program of this scope will require allocation of dedicated resources on the part of NMFS to achieve success. We emphasize that this must be a new allocation of research funds and not merely a diversion of current freshwater salmon resources to the marine environment since continued study of the freshwater phase of salmon is important and, in some cases, critical to the achievement of our goals. Even with a major increase in resources, it is unlikely that NMFS will be able to address all of the objectives alone. Cooperative partnerships need to be forged with the fishing industry, academic institutions, and state and foreign research scientists and managers to draw on their resources and expertise. A review panel made up of academic, NMFS, and other agency personnel should be established and should meet regularly to monitor progress and suggest course corrections as the program matures. New activities should be closely integrated, where possible, with existing programs within NMFS (e.g., the Ocean Carrying Capacity program at the Auke Bay Laboratory) and on the outside (e.g., GLOBEC Northeast Pacific Program, Canadian Marine Survival of Salmon Program, Canadian West Coast GLOBEC Program, PICES Climate Change and Carrying Capacity Program, and similar programs within other NPAFC member countries). These programs have the potential to contribute fundamental information (e.g., ocean models, primary productivity measurements, and zooplankton production estimates) that may be beyond the capabilities of the NMFS program.

Information on the environment is not widely used in salmon management in the United States; only recently have some applications been made to groundfish management (Boehlert and Schumacher 1997). We hope that by gaining an understanding of the linkages between salmon and the environment in which they live, useful information can be provided to managers to help forecast run size or optimal fishery locations. We advocate preserving of the diversity of salmon life histories that have evolved over time to adapt to changing ocean conditions (Bisbal and McConnaha 1998). Knowledge gained in the early life history of salmon may aid hatchery managers in their attempts to "naturalize" hatchery practices to mimic natural processes. Society as a whole will benefit if the knowledge we gain can reverse the decline of many salmon stocks and, at the same time, reduce adverse impacts to communities dependent on fishery resources (National Research Council 1996).

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