Decadal climate cycles and declining Columbia River salmon

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Abstract - This paper explores the effects of the interaction of anthropogenic trends and climate cycles on salmon declines in the Columbia and Snake river basins. A basic population model, including anthropogenic and environmental factors, is discussed and literature relating decadal scale climate patterns and the response of the North Pacific ecosystem is reviewed. From this background a ratchet-like decline in Columbia and Snake river salmon production resulted from the interactions of human activities and climatic regime shifts. These interactions are illustrated using hundred year patterns in spring chinook salmon (*Oncorhynchus tshawytscha*) catch, the Columbia River hydroelectric generating capacity, and a climate index characterizing the shifts between a cool/wet regime favorable to West Coast salmon and a warm/dry regime unfavorable to West Coast salmon. A half century correlation of the climate index and chinook catch suggest that a favorable climate regime counteracted detrimental impacts of hydrosystem development between 1945 and 1977, while an unfavorable climate regime negated beneficial effects of salmon mitigation efforts after 1977. This hypothesis is elaborated by a comparison of changes in the climate index relative to changes in Snake River salmon survival indicators.

Proposed Snake River salmon restoration plans are considered in terms of this counteractive effects hypothesis. The recent declines of salmon stocks have led a number of groups to propose plans that discontinue the present recovery actions, especially transportation of juveniles salmon around the dams. This paper hypothesizes that salmon recovery efforts, in part, have been limited by recent poor climate/ocean conditions. If this hypothesis is true, then eliminating the transportation program could be detrimental to fish. If the hypothesis is false, then eliminating transportation may be a viable recovery measure. In either case resolving the issue of counteracting processes is essential prior to making major changes to the hydrosystem operations.

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The catch of Columbia River chinook salmon (Oncorhynchus sp.)has declined over this century (Fig.1) and recently has reached record low levels with many stocks extinct and others on the brink of extinction (Stouder et al. 1997). The decline, from over 10 million to under 2 million adult fish, has been oscillatory and is the result of both natural and anthropogenic factors (Lichatowich and Mobrand 1995). Three major anthropogenic factors are generally mentioned: 1) loss by fishing; 2) loss of spawning and rearing habitat from agriculture, grazing, logging, mining and dams; and 3) loss during river migration related to passing through the dams and reservoirs of the hydrosystem (Ebel et al. 1989, Wissmar et al. 1994). In addition, the decline has been affected, sometimes enhanced and sometimes diminished, by the natural cycles of the climate and ocean. In this paper I consider the interactions of these factors. I first discuss the theoretical basis for the interaction of anthropogenic and natural processes, especially those involving climate. I then review information on climate regime shifts and the response of the North Pacific ecosystem. I then focus on the Columbia River system and how the climate has confounded our understanding of the decline of the salmon stocks in the system.

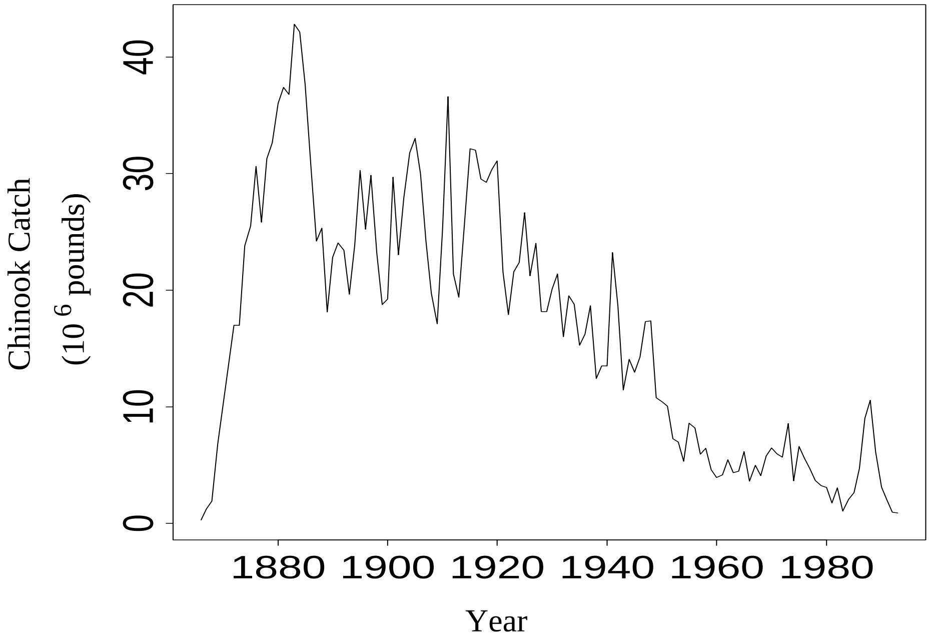

Fig. 1 Total chinook catch in the Columbia River system.

Methods

To establish a conceptual framework for the problem consider that a salmon stock decline is the result of cumulative and cyclic factors. Assume that the cumulative degradation of a stock is the result of anthropogenic processes while the cyclic processes are typically the result of natural environmental processes drive ultimately by a climate/ocean interaction. In terms of a stock recruitment equation, natural and anthropogenic factors are added to traditional density dependent and independent mortality terms giving

$$R_t = a\, S_t\, e^{-\alpha(t) - \beta(t) - bS} \qquad (1)$$

where R_t is the recruitment of fish into the stock from brood year t, S_t is the stock size in year t, $\alpha(t)$ is a mortality rate due to anthropogenic factors, $\beta(t)$ is a rate of decline from natural environmental time varying factors and a and b are the Ricker density independent and density dependent mortality factors which are taken to be time independent for this example.

In the traditional fisheries management paradigm $\alpha(t)$ and $\beta(t)$ are ignored and the parameters a and b are assumed constant with variations due to random processes. This simplified two parameter model (based on a and b) has outlived its usefulness for stock management, especially when a need exists to separate the impacts of human actions from climatic variations. In its place and number of approaches have been suggested to included additional factors. Adkins et al. (1996) outlined three approaches to evaluate climate effects on stocks. The first approach, designated as the “effect of climate variables method” explicitly includes climate variables in the spawner recruitment curve. In terms of eq(1) this is formulated as $\beta = c_i\, E_t$ where i designates stock specific variables and t designates time specific variables, c is a stock specific coefficient, and E is a time specific climate variable, such as temperature. The second method, designated the “one-time shift method”, involves using one set of the stock recruitment variables before a climate regime shift and a second set of variables after the shift. The equation then has an a b set for each regime and $\beta = 0$. The third method, called the “common influence method”, involves defining a common climate factor for a number for stocks and then fitting eq(1) in a multiple regression for stocks sharing the common effect through $\beta(t)$, which varies over time.

The model must be expanded to account for the anthropogenic effects. In the Columbia River the cumulative impacts of dams, overfishing, irrigation and intensive land use are significant factors contributing to the decline of stocks. To illustrate how these factors in principle alter the stock recruitment system assume in eq(1) that $\alpha(t)$ is a linearly increasing function with time so the population exhibits a gradual “slide” towards extinction (Fig.2). This description is inadequate though to assess the significance of cumulative anthropogenic processes when they occur along with climatic cycles. When cyclic natural and cumulative anthropogenic variations combine, the stock decline will assume a “ratchet” like character where the stock increases and decreases with the periodicity of the natural cycles. Over a number of cycles, though, the population declines (Lawson, 1993, Lichatowich and Mobrand 1995). This pattern is illustrated in eq(1) with α linear increase in $\alpha(t)$ and a sin wave in $\beta(t)$. The resulting population has a ratchet pattern as it declines to extinction (Fig.2). If the population is only observed within the period of an environmental cycle, identifying the contributions of the natural and the anthropogenic changes to the decline are difficult to assess.

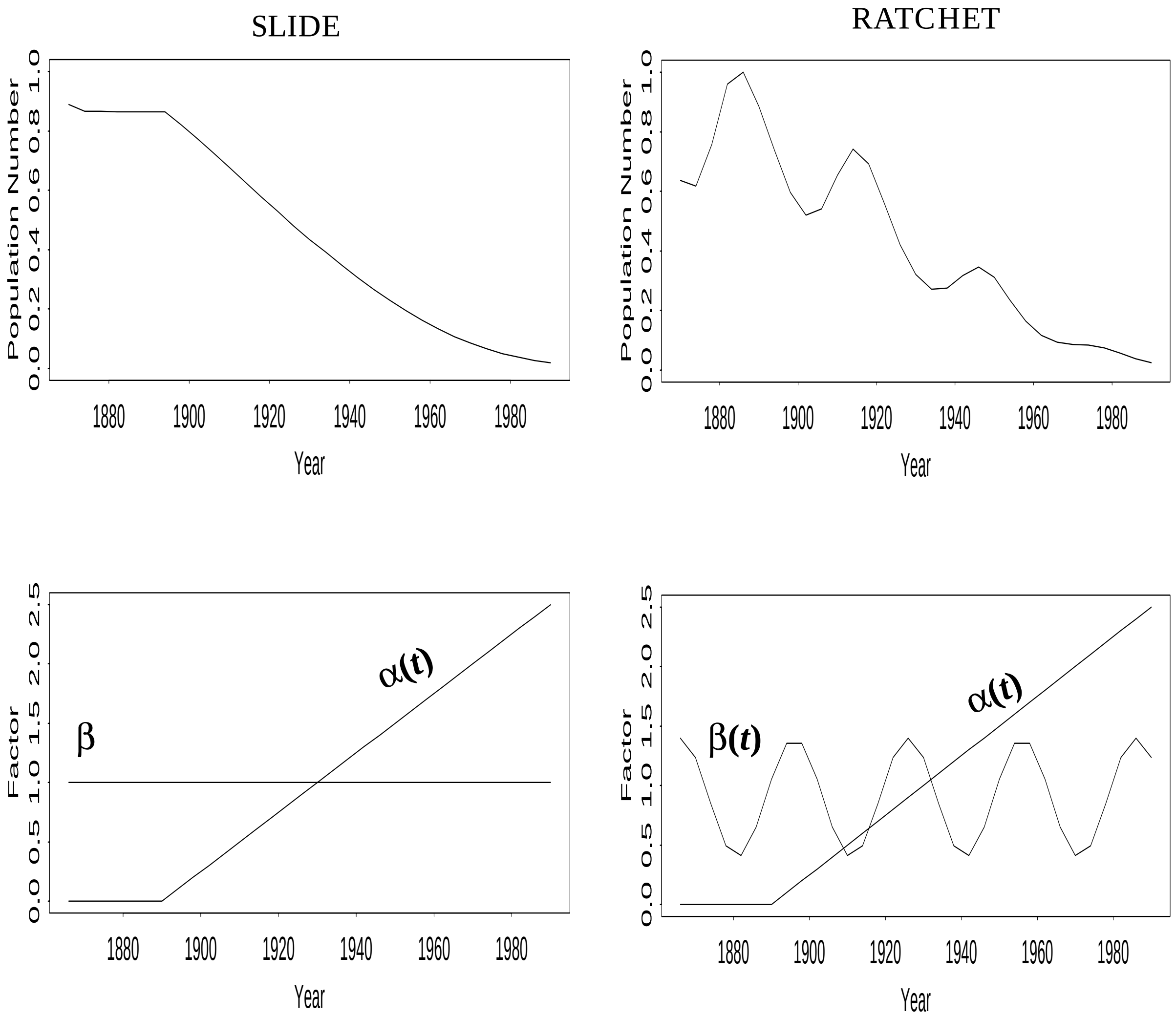

Fig. 2 Example of salmon decline under slide and ratchet processes. A population extinction slide is driven by increasing cumulative anthropogenic impacts, α(*t*), and a constant climatic effect, β. The population ratchet to extinction is driven by increasing cumulative anthropogenic impacts, α(*t*), and a climatic cycle β(*t*).

To explore this system in the context of a fishery consider that the cumulative human impact results from direct exploitation of the population and by indirect impacts, such as degradation of the habitat. In either case, the anthropogenic based trend typically evolves in three stages (Fig.3). The first stage (I) is *expansion* in which the population is directly or indirectly affected without regard to the consequences. In the second stage (II) activity is controlled through *regulation* to achieve some purpose such as to maximize yield or to distribute the economic benefits of the resource. If the regulation does not sustain the population, the third stage (III) follows in which the population's existence is *threatened* and mitigation actions are taken to recover the population.

For populations declining in a ratchet pattern the threatened stage is entered after the anthropogenic factors, acting over a long term, finally depress the population to a critically low level at which the natural fluctuation can drive it toward extinction. Under this scenario the natural place to define the beginning of the *threatened stage* is when the population is either at a high point or appears to have stabilized its abundance. From this *threatened abundance,* $N_{\text{threatened}}$, the decline in the natural factors drive the population toward N_{extinct} where genetic and ecological factors (Shaffer 1981, Soulé 1987, Thompson 1991) affect its sustainability. Thus $N_{\text{threatened}}$ is an early warning mark that, because of the uncontrolled nature of the natural cycle, is inextricably linked to N_{extinct}. Defining $N_{\text{threatened}}$ is not an easy matter though because it depends on the magnitude of $\beta(t)$, the continued rate of decline of anthropogenic factors, the effectiveness mitigation actions to reverse $\alpha(t)$, and the periodicity in the natural cycle. This example illustrates that extinction should be considered in the context of the cyclical variations and not just when a population is near extinction. This point was also emphasized by Lawson(1993).

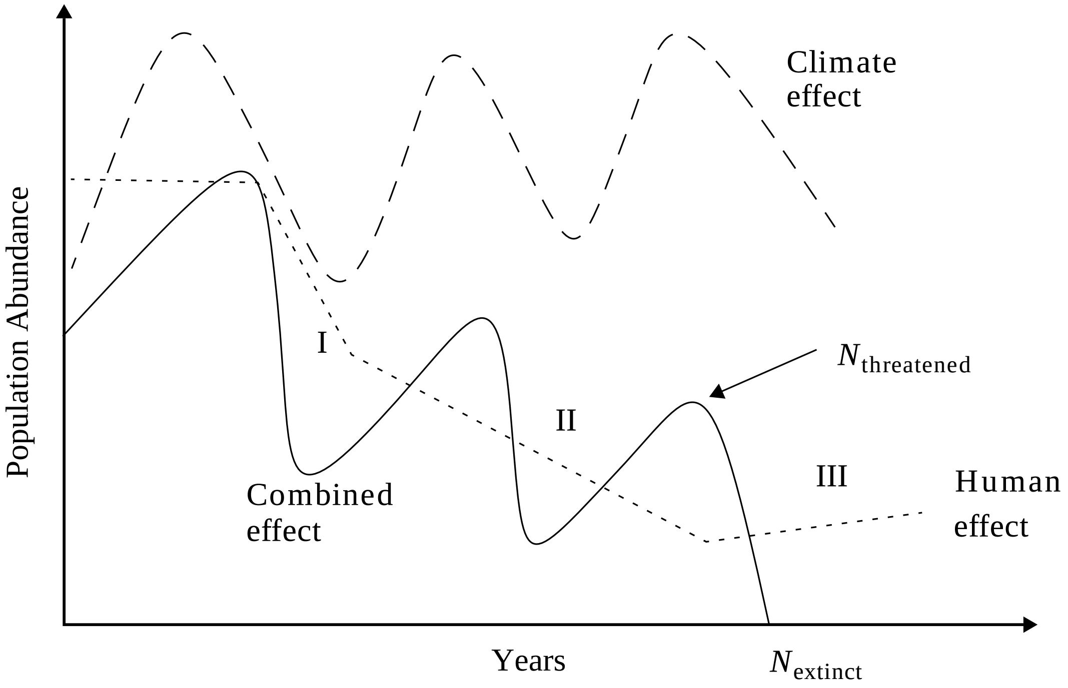

Fig. 3 A population extinction ratchet results from a natural cycle combining with cumulative anthropogenic use. Prior to exploitation the population varies in a natural cycle. Human use alters the population in three stages: (I) a period of expanding use, (II) a period of regulated use and (III) a period of threatened use where the actions may taken to recover the population. The population enters a threatened status, when the most recent peak falls below $N_{\text{threatened}}$. At population level N_{extinct} it is unlikely that the stock can be sustained.

The North Pacific ecosystem and decadal climate patterns

Considerable evidence indicates cycles in environmental conditions occur at many temporal scales and interact with many points in the salmon's life cycle. Before considering these interactions first consider evidence that oceanic and climatic fluctuations play major roles in the natural variations of the North Pacific ecosystem of which salmon are an integral member.

Fish and climate patterns

Multidecadal fluctuations in fish stock abundance have been observed for centuries (Rothschild 1995), but an appreciation of the importance of climate-fish fluctuations is relatively recent. The longest record of fish population fluctuations was obtained from a 2000 year sedimentary record off California. A surrogate record for the abundance of Pacific sardines and northern anchovy, inferred from scales in sediment cores, exhibited strong fluctuations over two millennia. A spectral analysis of the records revealed a peak at periods of about 60 years (Smith 1978, Baumgartner et al. 1992, Sharp 1992). The contribution of climate to these types of fluctuations was inferred from a similar pattern of climate indicators and sardine (*Sardinops*) catches around the Pacific basin (Kawasaki, 1984). One of the earliest papers on fishery oceanography documented the impact of the 1972-73 El Niño on the crash of the Peruvian anchovy fishery (Valdivia 1978). The general significance of climate on fisheries variability has also been the focus of other treatises (Smith 1978, Gantz 1992, Beamish 1995, and others).

Ocean/climate mechanisms

For the North Pacific studies detailing the decadal scale ocean variability and the ecosystem have mostly emerged since 1990 and were motivated by a striking shift in oceanic and biological conditions that occurred between 1976 and 1977. The oceanographic literature reported the shift as a change in the intensity of the winter time Aleutian Low pressure regime between 1976 and 1977, which was associated with a major and persistent change in oceanographic conditions (Fig. 4). The regime shift occurred as an abrupt change in the large-scale boreal winter patterns over the North Pacific. The change was marked by a southward shift and intensification of the Aleutian Low and prevailing westerlies over the mid-central and eastern Pacific (Graham 1994, Miller et al. 1994). In particular, the sea surface temperatures warmed.

The mechanisms driving these decadal scale interactions of the atmosphere and currents are not clearly understood. Studies have suggested they involve ocean-atmosphere couplings (Graham 1994), an 11 year variation in solar radiation (van Loon and Labizke 1994, Kerr 1995) and even the 18 year lunar cycle (Currie and Fairbridge 1986, Parker et al. 1995). Lagerloef (1995), following an idea proposed by Reed (1984), demonstrated that short period random forcing of the winds, decoupled from any long term cycles, can also produce a bidecadal periodicity in winds and ocean temperature anomalies. Theoretical papers have also discussed the importance of changes in the ocean heat flux, the thermocline depth (Graham 1994, Miller et al. 1994) and northward advection of warmer water along North America (Emery and Hamilton 1985, Bakun 1996). The warm coastal water of the warm/dry regime has been associated with a strong Alaska Gyre circulation which may be induced by weakening of upwelling on the west coast of North America (Hollowed and Wooster 1992). In contrast, the temperature change can also be considered as a cooling of the coastal water in the cool regime resulting from changes in nearshore winds related to the intensity of the Aleutian Low pressure system (Bakun 1996).

Although the warm and cool regimes appear to persist over about two decades, other periods have also been noted. Using a spectral analysis of twenty-one climate records over about 100 years Ware(1995) identified four dominant time scales: a 2-3 year (quasi-biennial oscillation), 5-7 year (El Niño - Southern Oscillation), 20-25 year bidecadal oscillation, and a poorly resolved, very low frequency oscillation with a 50-75 year period. Of his indicators, the bidecadal scale oscillation is most identified with the 1977 regime shift. A hundred year simulation of Northeast Pacific winter drift patterns and a 500 yr. record of tree ring growth data from Oregon exhibited cycles with a dominant period of 18 and 17.1 years respectively (Ingraham et al. in press). The tree ring data, similar to Ware's analysis, had a significant spectral peaks at 4 and 50 years (Richard A. Hinrichsen personal communication). Mantua et al. (1997) noted a decadal scale period with major climate shifts in 1925, 1947 and 1977.

Plankton response

Climate regime shifts also have had significant impacts on Northeast Pacific plankton. The 1977 regime shift, allowed warm sea surface water to move further northward and increased phytoplankton production in the Alaskan Downwelling Domain. At the same time the upwelling intensity in the West Coast Upwelling Domain and the associated phytoplankton production both decreased (Venrick et al. 1987, Ware and Thompson 1991). Current patterns also affected the advection of Subarctic Current and Alaskan Gyre zooplankton into the Domains. Abundant zooplankton levels in the Downwelling Domain have occurred with intense Aleutian Lows (warm regime) and abundant zooplankton in the west coast Upwelling Domain have occurred with weak Aleutian Lows (cool regime) (Wickett 1967, Brodeur and Ware 1992, McFarlane and Beamish 1992, Beamish and Bouillon 1993, Roemmich and McGowan 1995).

Several models have been proposed for the connection between climate and phytoplankton production, which in part drives changes in fish production. Venrick et al. (1987) postulated increased phytoplankton production is driven by increased vertical mixing during intense Aleutian Low. Roemmich and McGowan (1995) also hypothesized that, in the California current system, decreased zooplankton abundance after the 1977 regime shift was in part the result of suppression of nutrient supply by enhanced stratification. Gargett (1997) expanded on these hypotheses connecting stability, decadal fluctuations, phytoplankton growth and salmon. Because increased stability limits the surface layer nutrient flux, which limits plankton growth but restricts phytoplankton mixing out of the photic zone, vertical mixing has counteracting effects and so plankton growth should be optimized at some optimum 'window' of surface water stability. The window of optimum stability would change with latitude in Gargett's hypothesis to generate out-of-phase variations between northern and souther salmon stocks. Wong et al. (1995) proposed an alternative explanation for the phytoplankton growth relationship with the Aleutian Low intensity. The hypothesis is based on the recent findings that iron can become a limiting nutrient for phytoplankton production in the open ocean. The iron source is terrestrial, so North Pacific phytoplankton production could be correlated with atmospheric transport of iron from Asia. In this scenario, larger iron transport during an intense Aleutian Low would increase phytoplanknton production in the Alaskan Gyre.

Salmon response

Climate regime shifts are also associated with variations in salmon stocks. Trends in total salmon catches in the warm regime, post 1977, increased primarily from increased production of salmon from Alaska (Ware and McFarland 1989, Francis and Sibely 1991, Hollowed and Wooster 1992, Beamish 1993, Beamish and Bouillon 1993, Francis 1993, Francis and Hare 1994, Cooney et al. 1995, Mantua et al. 1997). The pattern was particularly strong with Bristol Bay sockeye (O. nerka), which jumped from catches, on the order of one million fish in the early seventies, to a record catch of 44 million sockeye in 1995 (van Amerongen 1995). The general trend was the same for pink (O. gorbuscha), coho (O. kisutch), and chinook (O. tshawytscha), from Alaska with upward trends beginning in 1976-77 and continuing into the eighties (Beamish 1993). These Alaskan catches remained high in the early 1990s. The pattern (comparing the 1950s to the 1980s) is also evident over a wide range of the Gulf of Alaska for sockeye, pink, chum (O. keta), coho, chinook salmon and steelhead (O. mykiss) (Brodeur and Ware 1995).

A trend in Alaskan chinook size also correlates with the regime shift, with decreasing sizes from 1951 and 1975 followed by an abrupt shift with increasing average chinook weight in 1977-78. This pattern first appeared in the northern stocks, with some southern stocks showing the increasing trend beginning in 1983, while other southern chinook stocks did not exhibit the increase (Beamish 1993). In contrast, declining size and increasing age at maturity were observed for chum salmon stocks from western North America between 1972 and 1992 (Helle and Hoffman 1995), and in the North East Pacific, halibut exhibited a decline in weight since 1976 (Parma 1995).

Latitudinal patterns

Evidence indicates that regime shifts have opposite effects on high- and mid-latitude biological populations. A century long record of sardine catch exhibited a striking coherence among several stock in the mid-latitudes of the Pacific Ocean. Isolated stocks of *Sardinops* spp., from Chile, Asia, and California had high catches about 1940 and 1990 with low catches in the 1970s. The catch statistics closely followed the sea surface temperature anomaly for the Pacific Basin (Kawasaki 1984, Sharp 1992). After 1977 the higher latitudes of the North Pacific exhibited increasing salmon catch trends from Alaska, Russia, Canada and Japan (Beamish and Bouillon 1993). West Coast salmon populations however, exhibited evidence of decline after the 1977 regime shift (Richards and Olsen 1993, Francis and Hare 1994). Furthermore, a 60-year data record between 1925 and 1985 showed that Gulf of Alaska pink and sockeye salmon catches were in phase, but they varied inversely with catches of Washington/Oregon/California coho (Francis 1993). The pattern was clear; Alaskan and West Coast salmon stocks oscillated out of phase. In the dry/warm regime Alaskan catches increased and the West Coast catches decreased and during the wet/cool regime the Alaskan catches decreased and the West Coast catches increased. This inverse Alaska and West Coast pattern was also evident in marine survival of hatchery reared salmon. Coronado-Hernandez (1995) estimated marine survival of 8596 coho, 11051 chinook, and 1389 steelhead tag groups from Alaska to California. In general, survivals declined over most of the geographical range and were particularly notorious in the late 1970s and in the late 1980s. Alaska coho exhibited the opposite trend with marine survival increasing in the late 1970s and 1980s.

Ecosystem mechanisms

The impact of regime shifts on salmonid marine survival and production is complex. In general, the Alaska stocks appear to be favored by the warm regime because of increased phytoplankton production, which increases the forage base of the fish. Factors that increase the fish forage base in the Downwelling Domain in the warm regime appear to decrease it for fish in the West Coast Upwelling Domain. In the cool regime the same factors appear to have the opposite effect. Gargett (1997) hypothesized the inverse relationship between salmon productivity in the Upwelling and Downwelling Domains results from opposite response of plankton productivity in the two Domains. Increased stability in the Upwelling Domain decreases phytoplankton productivity by decreasing nutrient flux into the surface layer. Increased stability in the Downwelling Domain increases phytoplankton productivity by confining the plants to the photic zone. To connect the dynamics to decadal scale processes Gargett hypothesized a mechanism relating water column stability to climate. In the North, water column surface stability is dominated by salinity and so a strong winter Aleutian Low increases Alaska rainfall and runoff which increases the salinity gradient and surface layer stability. In the South a strong winter Aleutian Low shifts winds to a more southerly direction which may increases temperature and inhibit upwelling.

Predators are also and factor, and environmental changes between warm and cool water regimes may affect the distribution and abundance of predators. In particular, the movement of warm water mackerel northward during a warm regime may decrease survival of West Coast salmon smolts during their ocean entry. Mackerel may move north with an stronger West Coast Davidson current associated with a strong winter Aleution Low.

Finally, the climate regime shifts also affect the freshwater habitat of salmon. The interaction can be either positive or negative depending on the patterns of rainfall, snowpack, temperatures and runoff. For example, floods during the fall spawning can disturb redds reducing egg survival while floods in late spring may increase turbidity and smolt migration speed which together decrease exposure to predators.

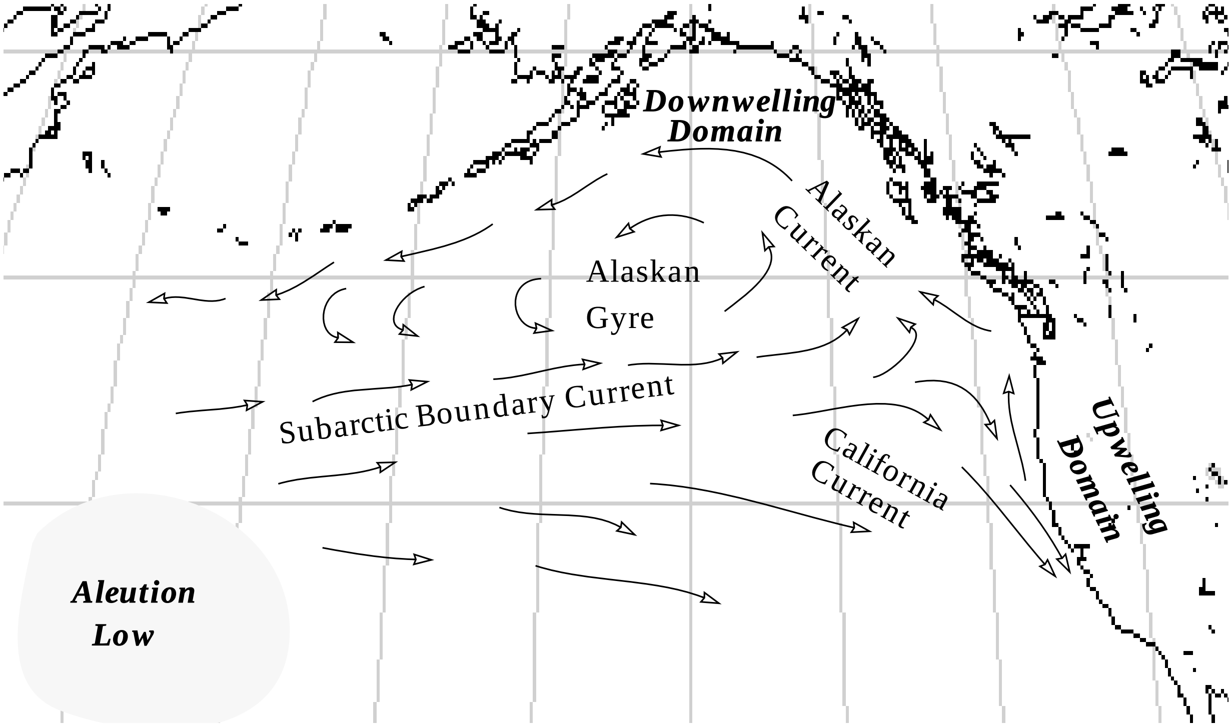

Fig. 4 Currents and production Domains. Years with an intense winter Aleutian Low shift the Subarctic current northward, strengthen the Alaskan current and increase the Downwelling Domain production. Years with a weak Aleutian Low shift the Subarctic current southward and strengthen the California Current and the Upwelling Domain production. Shifts occur on decadal scales.

Regime shift indicator

Relationships between climate and salmon are suggested in a variety of records. In these characterizations, a number of climate indicators have been used including the Kodiak winter air temperature (Francis and Hare 1994), the Central North Pacific winter atmospheric pressure index (Cayan and Peterson 1989), and the sea surface temperature anomaly based Pacific Decadal Oscillation (PDO) (Mantua et al. 1997) to name a few. Many other environmental changes, both physical and biological, are also correlated with decadal scale climate changes. Ebbesmeyer et al. (1991) found changes in forty environmental indicators correlated with the 1976 regime shift.

For comparison with Columbia River salmon, the Pacific Northwest Index (PNI) developed by Ebbesmeyer and Strickland (1995) is useful because it is a century-long composite index that characterizes Pacific Northwest climate patterns in both coastal waters and freshwater habitats. The PNI uses three measures: air temperature at Olga in the San Juan Islands, averaged annually from daily data; precipitation at Cedar Lake in the Cascade Mountains, averaged annually from daily data; and snowpack depth at Paradise on Mount Rainier on March 15 of each year. For each measure annual averages are normalized by subtracting annual values from the average of all years and dividing by the standard deviation about the average for all years.The three measures are averaged, giving a relative indicator of climate variations. Positive PNI values indicate warmer and dryer years than the average, and negative values indicate cooler and wetter years than the average. Over a 90 year record the running 5-year PNI average switches between warm/dry and cool/wet regimes on about a 20-year period. The cycle has a distinctive double-peak pattern with a strong regime shift followed by two weaker regime shifts and then another strong regime shift. The strong regime shifts in the PDO in 1925, 1947, and 1977 (Mantua 1997) are also evident in the PNI. If the pattern were to hold, the recent cooler wetter Pacific Northwest weather may be a weak regime shift which would be followed by a more intense period of warm dry weather. In support of an impending climate shift, Ingraham et al. (in press), evaluating a 500 yr. tree ring growth record and 100 year Gulf of Alaska winter surface drift simulation, suggest that the Northeastern Pacific climate recently shifted, or is due to shift, to the cool regime.

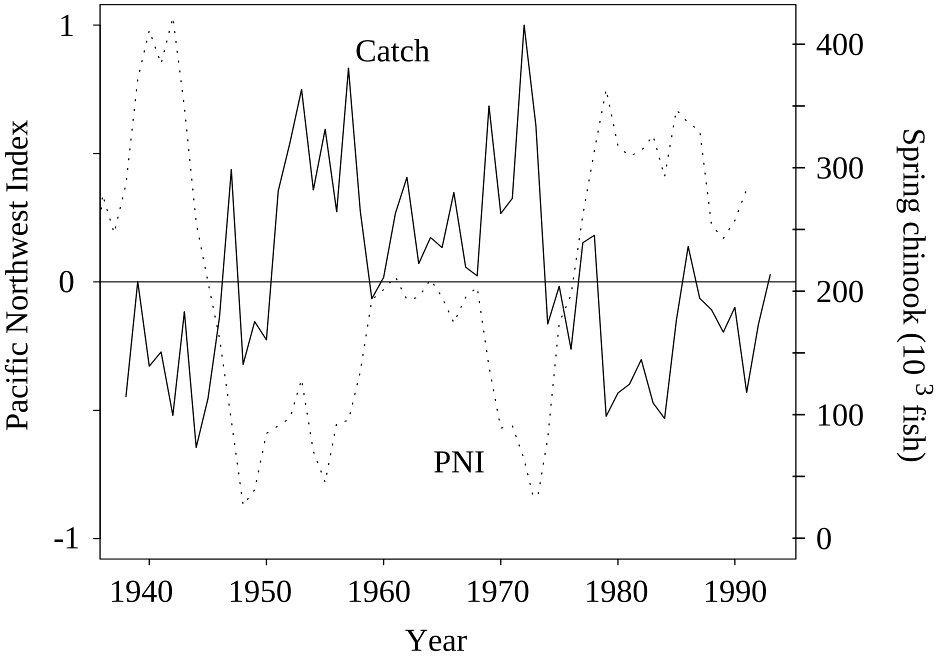

Fig. 5 Relationship of catch of Columbia River spring chinook vs. the PNI. Both indicators are expressed as 5 year running averages.

PNI and Columbia River Salmon

The evidence discussed above strongly suggests that salmon catch and climate cycles are correlated. Although catch is not a direct measure of abundance or survival, it does reflect abundance and is the only population information that spans the century. The PNI relationship with the Columbia River spring chinook catch (WDF and ODFW 1992) is especially compelling because of a strong coherence (Fig. 5). The evidence suggests that warm/dry Pacific Northwest climate regimes produce poor conditions for some Columbia River salmon and good conditions for Alaska salmon. The opposite effect, favoring Columbia River salmon, appears to occur in cool/wet climate regimes.

Climate and the hydrosystem

With these patterns established we can evaluate the combined impact of climate and the development of the Columbia River hydrosystem on salmon populations. Over the last hundred years three major climate shifts have occurred (1925, 1947, 1977) which in turn have significantly altered salmon survival. Embedded as a 50 year interval in the middle of this pattern the hydrosystem was developed. As hypothesized and illustrated in Fig. 3, climatic variations can mask anthropogenic impacts creating a complex history of salmon decline that is misunderstood if the climatic cycle is ignored. In particular, the patterns suggest that the climate cycle has masked both the negative impact of the Columbia/Snake River hydrosystem during its development and the positive impact of Columbia River mitigation measures implemented post-development.

To illustrate this idea of counteracting processes, consider the decadal scale cycle as represented by the PNI, the anthropogenic use of the river system as represented by the hydroelectric generating capacity, and the fish population as represented by the total Columbia River chinook catch (Fig. 6). To understand these trends consider that in the initial years of the Columbia River fishery, prior to 1925, the total harvest was relatively stable and the cool/wet climate pattern was favorable to fish. An approximate balance between chinook fish production and harvest likely existed. In 1925, when the climate changed to the unfavorable warm/dry pattern, the productivity declined, and in response salmon catch began its long decline. About 1947 the climate shifted to the cool/wet pattern favorable to fish and the rapid development of the hydrosystem commenced which was undoubtedly detrimental to fish. The climatic shifted back to the unfavorable regime in 1977, which was one year after the completion of the last dam on the Snake River.

After the completion of the hydrosystem attention was given to reducing fish mortality caused by the hydrosystem. Actions on adults include replacing lost habitat with hatcheries and installing fish ladders to pass adult salmon upriver. To improve survival of juveniles migrating though hydrosystem reservoirs additional water is released from storage reservoirs to increase flow and predators are removed in a bounty harvest program. To lessen the impacts of both dams and reservoirs, juvenile fish are collected at dams (starting 1975 in the Snake and 1979 in the lower Columbia) and barged to below Bonneville Dam, the lowest dam on the river. A series of changes have also been implemented to reduce turbine mortality including operating turbines near peak efficiency to reduce cavitation and removing the debris accumulated in the trashracks at turbine entrances (Williams and Matthews 1995). These changes increased survival of fish migrating from the Snake River, but the effect has in part been masked by the shift to an unfavorable climate regime in 1977.

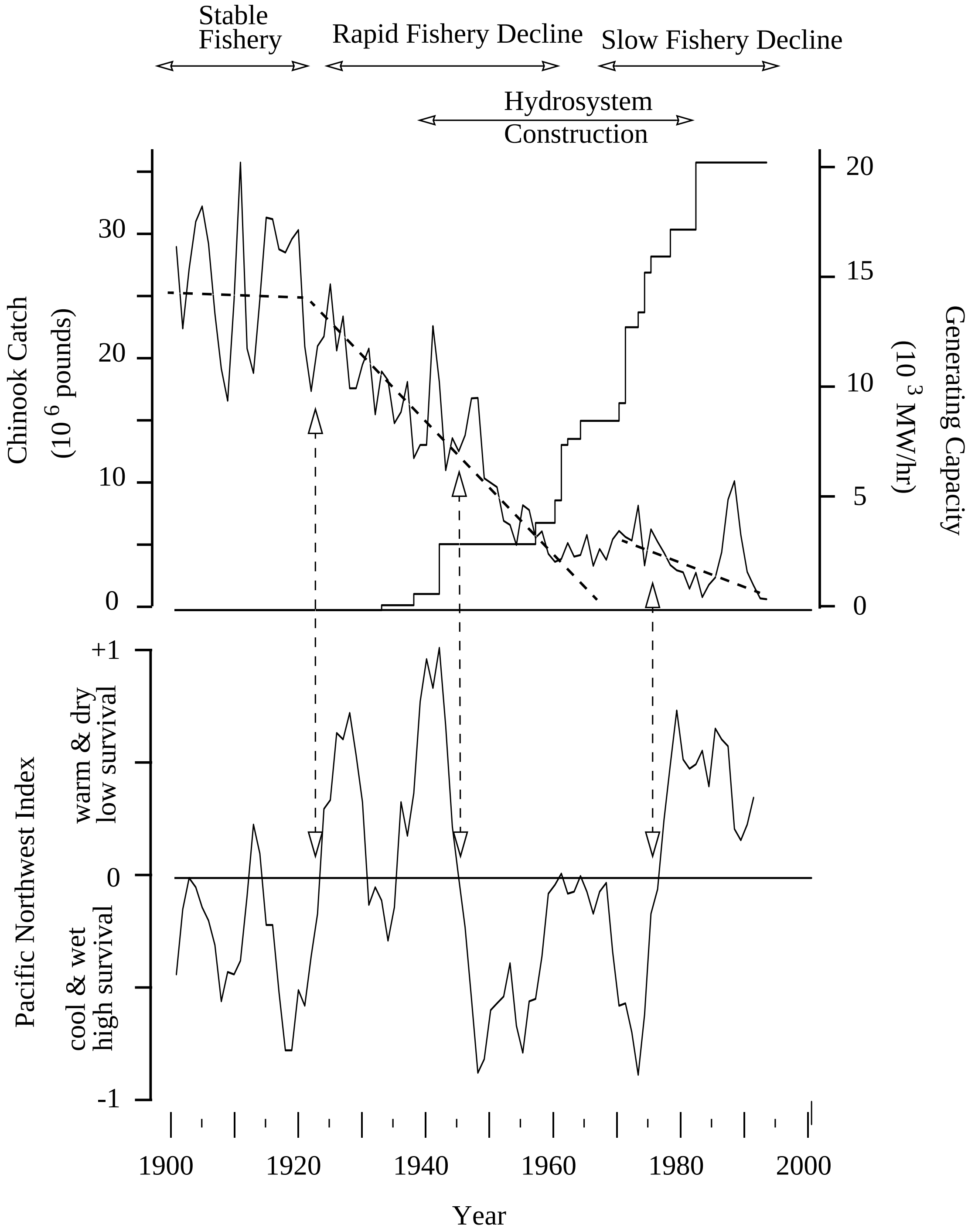

Fig. 6 Relationship of the PNI climate index, Columbia River spring chinook catch and hydroelectric capacity.

Interaction of processes

The scenario that the impacts of climatic and anthropogenic factors have been countervailing for a number of decades is based on a significant number of patterns observed over the entire North Pacific. Specific to the Columbia River though, the counteracting-factors hypothesis is also supported by patterns of modeled smolt survival and redd-count-based survival estimates which are correlated with the PNI pattern.

Salmon survival and climate patterns

Smolt hydrosystem passage survival over the past three decades was estimated using the CRiSP mainstem passage model (Anderson et al. 1996). The model accounts for smolt migration mortality from exposure to predators, dissolved gas supersaturation and dam passage. The model characterizes hydrosystem operations, fish transportation schedules, flow, temperature and dissolved gas for each day from 1966 through 1995. The model's reservoir mortality algorithm was calibrated with data from a predator consumption study conducted in the 1980s (Rieman et al. 1991) and dam passage mortality was calibrated with studies conducted over three decades and mortality from gas bubble disease was calibrated to laboratory studies. Fish migration rate was calibrated with fish travel time data collected from PIT tag studies conducted between 1989 and 1996 (Zabel and Anderson 1997). Model predictions were compared to over fifty spring chinook smolt survival estimates derived from mark recapture studies conducted between 1966 and 1996 over different reaches of the river and for different stages of construction of the hydrosystem. The predicted vs. observed survivals have a one-to-one relationship with $r^2 = 0.7$.

To characterize the hydrosystem impact on juvenile salmon over the past three decades, yearly survivals were determined between a Snake River tributary and the Columbia River estuary. The survival, including barge and in-river migrating fish was high in the late 1960s, dropped to very low values in the 1970s and then increased (Fig. 7). Between 1966 and 1969 fish encountered only Ice Harbor dam on the Snake River and three Columbia River dams. The model estimated survival was about 40%. In 1969 Lower Monumental Dam was put in service above Ice Harbor Dam. Because the dam was initially operated without turbines the entire river flow was spilled, creating gas supersaturation levels well above 130%. High spill and dissolved gas levels also occurred when Little Goose and Lower Granite dams were put in service with only half their turbines in 1970 and 1976 respectively. During these years hydro operations were not optimized for fish survival (Raymond 1979, Williams and Matthews 1995). To complicate matters, 1973 had extremely low flows resulting in longer fish travel times and increased exposure to predators. As a result of these construction and operation conditions the system survival of juvenile fish dropped to under 10%. Following this period, modeled system survival increased for two reasons. First, the supersaturation problems were solved at Snake River dams when full complement of turbines were installed. This allowed water to pass through turbines instead of being spill. Second, increased collection and transportation of smolts around dams increased survival resulting in a 60 to 70% survival of smolts to the estuary. In terms of river passage alone the model indicates that the survival in the 1990s is equal to the survival in the 1960s

These high estimates of survival depend on the rate fish survive transportation in barges. This estimate is based on experiments that compared the percent survival-to-adults of fish that were transported to the percent survival-to-adults of fish that migrated through the river. The ratio of smolt-to-adult survivals when combined with in-river survival estimates provides an estimate of transportation survival. For spring chinook transportation survival was estimated for to be 89% in this analysis. That is, 89% of the fish transported through the hydrosystem are estimated to survive juvenile passage.

To explore the counteracting factors hypothesis, a measure of smolt-to-adult survival for Snake River spring chinook has been used (Raymond 1988, Schmitten et al. 1995). In the measure the smolt out-migration population size is derived from counts of adult spawners estimated from redd counts on the spawning grounds. The returning adults are estimated from adult escapement counts. The resulting smolt-to-adult survival includes smolt migration survival, survival of adults in the ocean, survival in upriver migration and their spawning success. This survival was high in 1965. It declined and remained low between 1970 the early 1990s, which are the most recent stock recruitment data (Fig. 7).

Finally Fig. 7 shows a normalized form of the PNI where high values represent the cool/wet regime and low values represent the warm/dry regime. Although it is not possible to identify what parts of the life history is most affected by conditions characterized by the PNI, studies of climatic effects on the North Pacific ecosystem (Pearcy 1992) suggest a survival correlation with the PNI may be the result of conditions affecting smolts during ocean entry.

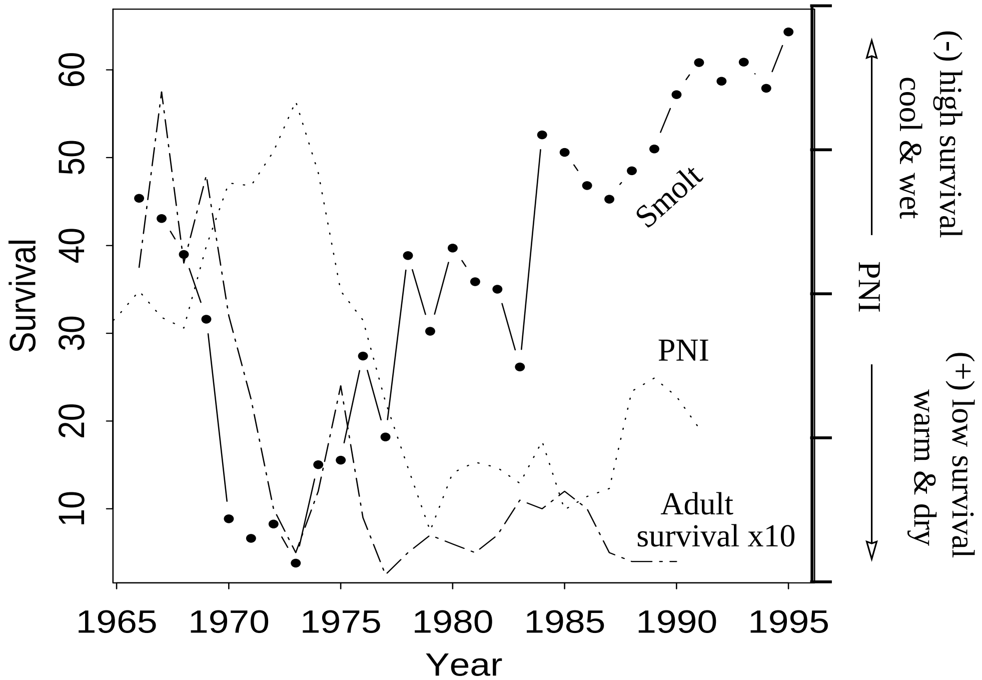

Fig. 7 Trends of PNI climate indicator, CRiSP estimated smolt migration survival from the Snake River Basin to the Columbia River Estuary and a measure of the smolt-to-adult (x10) survival of Snake River fish.

Over the past three decades climate and river conditions had nearly opposite trends relative to smolt survival (Fig. 7). In the early 1970's the PNI climatic index indicated a cool/wet Pacific Northwest climate, favorable to spring chinook, while the smolt river passage survival was at its all time low. After 1975 the climate indicators declined, indicating a shift to warm/dry salmon unfavorable climate, while the river survival steadily increased. The opposite trends in the PNI and smolt survival suggest that climate and hydrosystem impacts on have counteracted each other over the past several decades. When smolt river survival was lowest, the climate was most favorable to ocean survival, and when the river survival was highest the climate was least favorable to salmon survival. The counteraction between hydrosystem and climate survivals should be reflected in the smolt-to-adult survival. This is in fact the case, with the smolt-to-adult survival trend following the smolt passage survival through 1975 and then remaining low with warm/dry PNI values.

Quantifying climate and anthropogenic processes

Although evidence strongly suggests that decadal scale processes and anthropogenic changes interact and complicate the interpretation of the causes for fish stock variations, it is another matter to separate the effects of each process using historical data or new experiments. To evaluate the impact of climatic and anthropogenic variables the climate variables can, in principle, be defined by the three methods identified by Adkins et al (1996). The impact of anthropogenic actions though, needs to be quantified by an "anthropogenic effect index." For example, the hydrosystem impact might be quantified by the number of dams fish pass, an estimate of passage mortality, or specific to the Columbia River system, the percent of fish transported. We may express the anthropogenic impact of dams on mortality by setting $\alpha(t) = c_i D_{i,t}$ where D is the number of dams a fish passes and this may change as dams are constructed. Anthropogenic and climate impacts might also be separated through a "differential influence" method incorporating stocks with a common climate influence but different anthropogenic influences. For the Columbia River this method requires information on stock passing through different numbers of dams but experiencing a common environmental factor. The two methods are also distinguished in the grouping of stocks used in the analyses. The effects of dams method groups stocks with common climate and anthropogenic influences and seeks to resolve the two factors by the temporal changes in the indices. For the Columbia River this means stocks from a single subbasin are used in an analysis. In the differential influence method stocks from several subbasins are combined. This requires spawner recruitment data from in the Snake River and from the lower Columbia stocks.

Several problems make separating of climatic and anthropogenic factors difficult with these techniques. An effects of dam method may demonstrate a relationship between stock declines and increases in dam indices but a correlation over time does not, of itself, imply the dams are responsible for stock decline As such, if actions were taken to remove dams, it is not clear that the stocks decline would reverse. A biological basis is required to connect indices to processes that alter stock productivity. In the differential method the assumption that stocks experience similar climate influences is required, but if the assumption is violated any differential climate impacts would bias estimate of the anthropogenic impact. These types of problems become significant when identifying the potential effect of mitigating the anthropogenic factors through actions.

Conclusions

In this paper I illustrate the importance of resolving the interaction of anthropogenic and natural factors when exploring the historical causes of a population decline and in planning stock recovery actions. This analysis shows that the ratchet-like extinction process proposed by Lawson (1993) and Lichatowich and Mobrand (1995) is relevant to Columbia River salmon. It is clear that Columbia River salmon declines are the result of a long history of development of the river system which has been modified by three major climate regime shifts. A significant drop in Columbia River salmon harvest about 1925 (Fig. 1), marked the beginning of a long stock decline well before the construction of the hydrosystem. This event was likely the result of overharvest being accentuated by the 1925 climate/ocean shift from favorable to unfavorable conditions. The shift of the ocean/climate regime to fish favorable conditions in 1947 counteracted the detrimental effects hydrosystem construction between 1932 and 1977. A shift back to fish unfavorable conditions counteracted the mitigation efforts over that last twenty years.

This interaction of climate and dam operations has more than historical significance: by ignoring climate cycles salmon managers may misinterpret the effectiveness of the recent stock recovery efforts, and in particular they underestimate the benefits of smolt transportation. Several proposed recovery plans for the endangered Snake River salmon (Schmitten 1995, CRITFC 1995, Williams et al. 1996) directly or indirectly assume that the past twenty years of salmon mitigation efforts have been ineffective, since salmon runs have continued to decline. These plans, to differing degrees, propose to de-emphasize fish transportation and advocate in-river passage using higher flows from storage reservoirs, spilling water at dams, and drawing down the reservoirs behind the dams to improve water velocity and fish habitat. The premise is that these actions will mimic the natural river conditions that occurred in the past when fish runs were larger. Whatever the effect of these proposed actions, it is in my opinion, unlikely that they will approach the benefit of a climatic shift back to a fish favorable cool/wet regime. Plans that eliminate beneficial programs, such as fish transportation, will only worsen the present situation.

In a larger perspective the consequences of ignoring the complex and long-term interactions of climatic cycles and anthropogenic actions and focusing instead on simple short term explanations are significant. In particular, when dealing with endangered species a narrow focus may lead to misguided beliefs on the success and failures of restoration efforts. It is only through a long term ecological perspective, embracing natural and anthropogenic interactions, that society can assess the actual impact of human activities and realistically identify options and limitations faced when correcting environmental damage accumulated over decades.

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