PERSPECTIVE:
FISHERIES MANAGEMENT

Climate Change, Ecosystem Impacts, and Management for Pacific Salmon

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ABSTRACT: As climate change intensifies, there is increasing interest in developing models that reduce uncertainties in projections of global climate and refine these projections to finer spatial scales. Forecasts of climate impacts on ecosystems are far more challenging and their uncertainties even larger because of a limited understanding of physical controls on biological systems. Management and conservation plans that explicitly account for changing climate are rare and even those generally rely on retrospective analyses rather than future scenarios of climatic conditions and associated responses of specific ecosystems. Using past biophysical relationships as a guide to predicting the impacts of future climate change assumes that the observed relationships will remain constant. However, this assumption involves a long chain of uncertainty about future greenhouse gas emissions, climate sensitivity to changes in greenhouse gases, and the ecological consequences of climate change. These uncertainties in forecasting biological responses to changing climate highlight the need for resource management and conservation policies that are robust to unknowns and responsive to change. We suggest how policy might develop despite substantial uncertainties about the future state of salmon ecosystems.

Cambio climático, impactos a nivel ecosistema y manejo del salmón del Pacífico

RESUMEN: A medida que el cambio climático se intensifica, existe un creciente interés en desarrollar modelos que reduzcan la incertidumbre en las proyecciones del clima global, y llevar estas proyecciones a escalas más finas. El pronóstico de los impactos del clima sobre los ecosistemas es más difícil de abordar y la incertidumbre asociada es aun mayor porque se tiene un entendimiento rudimentario sobre los controles físicos en sistemas biológicos. Son pocos los sistemas de manejo y conservación que consideran explícitamente el papel del clima, e incluso éstos se basan en análisis retrospectivos más que en escenarios futuros de condiciones climáticas y las correspondientes respuestas a nivel ecosistema. Al utilizar relaciones biofísicas preestablecidas como guía para predecir los impactos de cambio climáticos, se asume que dichas relaciones permanecerán constantes. Sin embargo, esta suposición implica una larga cadena de imprecisiones con respecto a la intensidad de futuras emisiones de gases de invernadero, sensibilidad climática a los cambios en estos gases, y las consecuencias ecológicas del cambio climático. La incertidumbre del pronóstico de las respuestas biológicas a un clima cambiante, resaltan la necesidad de políticas de manejo y conservación que sean suficientemente robustas a esas incógnitas y sensibles al cambio. Se sugiere cómo pueden desarrollarse tales políticas a pesar de la importante incertidumbre que existe en torno al estado futuro de los ecosistemas que albergan al salmón.

OVERVIEW OF SALMON RESPONSES TO CHANGING CLIMATE

Pacific salmon are icons of the natural and cultural heritage of coastal nations throughout the subarctic North Pacific Ocean (SNPO). Since the 1960s, scientists across all nations of the SNPO have greatly advanced understanding of Pacific salmon and their habitats. During this time period, environmental conditions of the SNPO also have shifted substantially in response to inter-decadal climate variability and longer-term warming trends (e.g., Schindler et al. 2005). Initial syntheses of these data have begun to shed light on how salmon and their ecosystems respond to changing climate.

Pacific salmon are affected by climate change across a hierarchy of coarse and fine spatial and temporal scales; each of these scales has distinct implications for development of policy that will be robust to future climate change. At the scale of the entire SNPO (Figure 1), biomass of Pacific salmon has increased substantially over the last century (Figure 2; Eggers 2009 in press), coincident with increases in global temperatures (IPCC 2007). This increased salmon production has been especially pronounced since the mid-1970s (Mantua et al. 1997; Beamish et al. 2008). However, trends in both climatic conditions and salmon production have not been uniform across the SNPO. In western North America, inter-decadal patterns of salmon production in northeastern stocks (i.e., Alaska) are out of phase with production regimes for stocks in the conterminous United States and Canada (Figure 3). This variation in production coincides with warming trends in salmon watersheds and nearshore marine waters in western North America, but cooling trends in the open waters of the interior North Pacific Ocean where most salmon feed and mature (Mantua et al. 1997; Hare et al. 1999).

At still finer spatial scales, stocks entering the ocean within 500-800 km of one another have weakly coherent responses to changes in local oceanographic conditions (Mueter et al. 2002; Pyper et al. 2005). This regional coherence in productivity is most correlated with regional variation in sea surface temperatures (Mueter et al. 2002). However, at the scale of individual populations, responses to regional shifts in climatic conditions are diverse (Figure 4; Peterman et al. 1998; Hilborn et al. 2003; Crozier and Zabel 2006; Rogers and Schindler 2008). Further, salmon species vary considerably in their responses to regional climate changes (Hare et al. 1999). Identifying features of the environment and of salmon populations that produce the diversity of salmon responses to regional climate forcing is critical because these are the scales at which most management and conservation activities operate.

Policies for managing salmon in the face of climate change must change if we hope to meet our conservation and management goals. Our ability to accurately predict climate impacts on salmon ecosystems is incomplete and unlikely to improve to the point of accounting for the regional response diversity noted above. Policies must be robust to these uncertainties rather than reliant upon prescriptive forecasts of climate and associated ecological conditions. Some such management strategies have been suggested as ways to account for climatically-driven changes in salmon production, without the need to understand the intricacies of climate impacts on salmon ecosystems (e.g., Walters and Parma 1996; Peterman et al. 2000). For example, Walters and Parma (1996) showed that a constant harvest strategy (i.e., one that exploits a constant proportion of stock each year) performs remarkably well at tracking long-term fluctuations in stock productivity, as would be caused by climate change. The information needed to develop such a strategy relies heavily on our ability to forecast year-to-year variation in abundance but does not necessar-

Figure 1. Map of the distribution of salmon in the Subarctic North Pacific Ocean (SNPO). Letters and corresponding arrows depict the location and rough spatial scales over which data from Figures 3 and 4 were summarized.

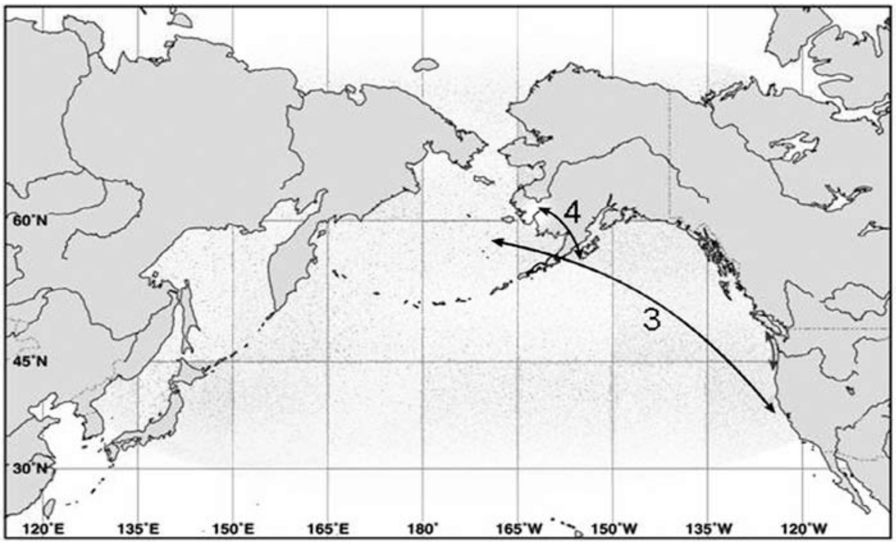
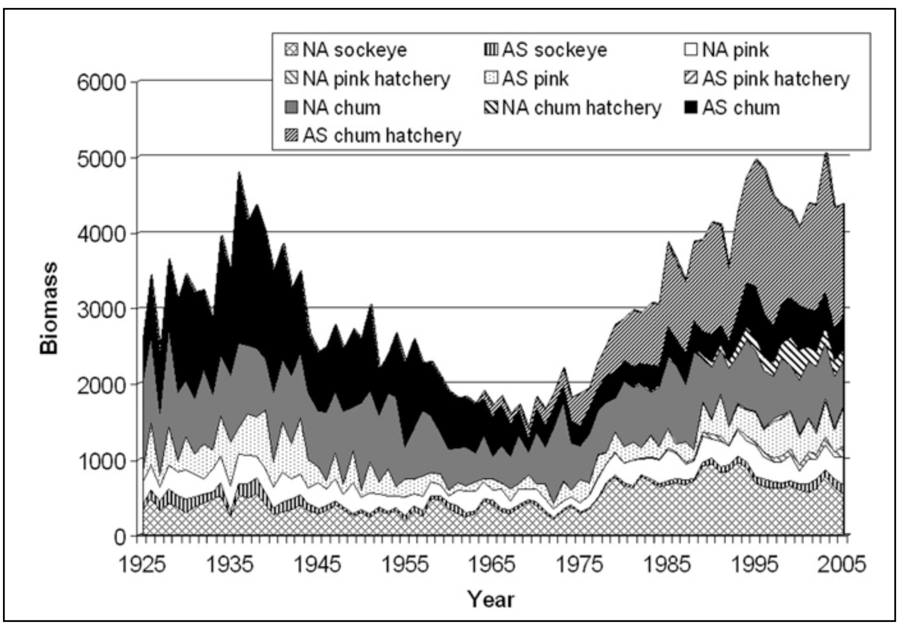


Figure 2. Total biomass (thousands of metric tons) of chum (*Oncorhynchus keta*), sockeye (*O. nerka*), and pink salmon (*O. gorbuscha*) inhabiting the SNPO (stippled area in Figure 1) from 1925–2005. Data are separated by species, continent of origin (North America [NA] versus Asia (AS), and hatchery versus wild stocks). Not all hatchery contributions are known with high certainty (e.g., Russian pink salmon) so these are combined with the wild components. Data are from Eggers (2009 in press).



ily rely on an intricate understanding of the processes causing climatically-driven variation. Given our limited predictive capacity, what information about the links between salmon and climate is useful to current policy? In particular, how might policy to address climate impacts on salmon embrace the hierarchy of spatial and temporal scales that characterize salmon responses to a changing environment?

Figure 3. Standardized anomalies of salmon harvests along the North American west coast from 1925–2005. Data were smoothed with a 5-year running mean. Abbreviations are: ch = Chinook salmon (*O. tshawytscha*), co = coho salmon, so = sockeye salmon, pi = pink salmon, BC = catch from British Columbia, US = catch from US lower 48 states, AK = catch from Alaska).

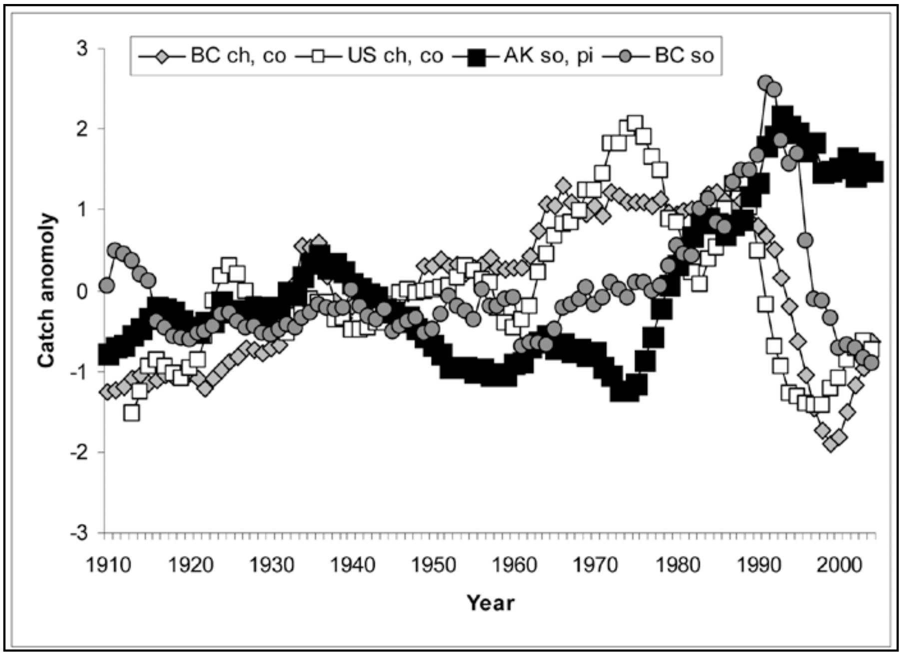
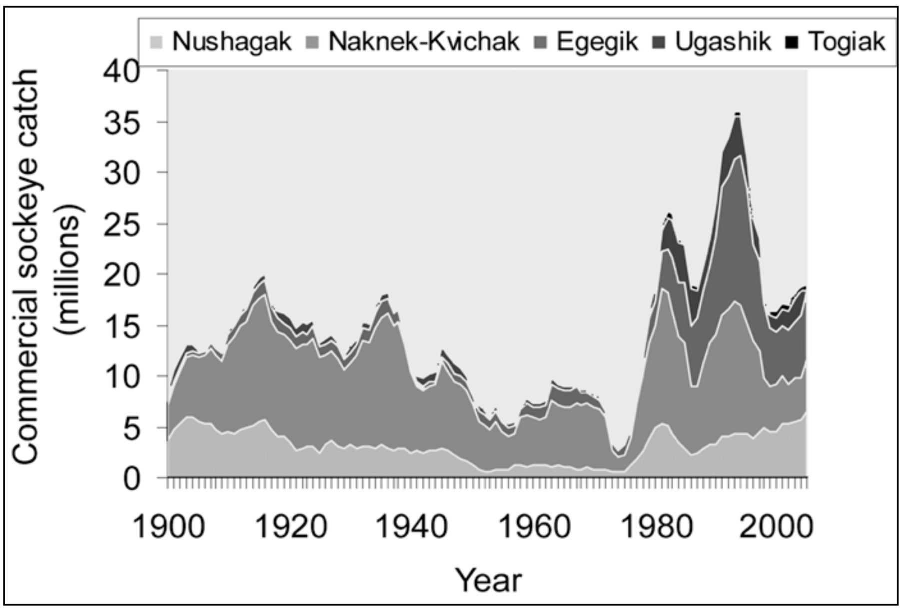


Figure 4. Sockeye salmon (*O. nerka*) commercial catch (millions of fish) from Bristol Bay, Alaska, from 1893–2006, apportioned to five fishing districts associated with the major rivers of this region (updated from Hilborn et al. 2003). Data are smoothed with a 5-year running mean.



The need for SNPO-wide salmon-climate policy

Improved salmon-climate policy is needed at all of the spatial scales described above. First, we believe that proactive policy development at the scale of the entire SNPO is needed to help minimize future climate-induced political conflicts over the use of limited prey resources by salmon from different nations of the SNPO. At the scale of the entire SNPO, increases in salmon biomass largely reflect increasing numbers of hatchery-released salmon from Eurasia (Figure 2, Eggers 2009 in press) that compete with salmon from North American rivers when they overlap in international waters (Kaeriyama and Edpalina 2004; Ruggerone et al. 2005). This surge in salmon production was concurrent with a general cooling of North Pacific offshore habitat where salmon achieve most of their growth (Mantua et al. 1997; Hare et al. 1999). If the increasing trend in biomass is dependent upon the cooling trends in this offshore ecosystem, it is not likely to persist with ongoing climate warming. Thus, the institutional expectation of the SNPO's capacity to produce salmon that has developed during the last few decades may prove overly optimistic as global atmospheric and upper-ocean temperatures continue to increase. In fact, capacity may decline if thermal characteristics of offshore habitat eventually switch trajectories and, consistent with global climate model projections, the upper ocean begins warming. More extensive use of the Arctic Ocean by Pacific salmon may partially offset any diminished capacity of the SNPO. Nevertheless, international coordination of management of the open-ocean commons used by Pacific salmon needs refinement to address potential climate-driven changes in productivity. There is currently no coordinated vision for use of the SNPO (Holt et al. 2008).

Climate policy at regional scales

At intermediate (regional) spatial scales, policies that govern maintenance of habitat quality and harvest strategies could be modified to more appropriately account for complex stock structure and variation in climate impacts on different habitats used by salmon. Multi-decadal regimes of high salmon production (Beamish et al. 1999) due to favorable ocean conditions may mask the erosion of freshwater and estuarine habitat quality, and within-stock biodiversity, that only become evident once productivity in the ocean decreases. For example, fisheries for Oregon coho salmon (*Oncorhynchus kisutch*) appeared to be robust and sustainable from the 1950s into the mid-1970s. During this period, hatchery programs grew rapidly and replaced wild stocks as the principal producers of juvenile coho salmon (Pearcy 1992). Intense harvest rates that seemed appropriate for hatchery stocks during periods of exceptionally high marine survival proved too high for the long-term sustainability of wild stocks. In 1977, a shift in the state of the Pacific Decadal Oscillation generated a 20-year period of unfavorable ocean conditions for Oregon coho salmon. The abundance of both hatchery and wild coho salmon adults plummeted, sending coho salmon populations and their fisheries into a decline from which they may be only beginning to recover. Accordingly, despite their knowledge that hatcheries were eroding the complex stock structure of wild coho salmon that had evolved for millennia, a 20-year period of high marine survival rates led fishery managers to mistakenly believe that large-scale hatchery production could sustain intense fisheries (Lichatowich 1999).

Further, Oregon coho salmon provide a compelling example of situations where favorable climatic conditions and high survival in one habitat (e.g., ocean) can obscure the degradation of other habitats (e.g., freshwater systems). For example, degradation of freshwater habitats can occur during periods of favorable ocean conditions that produce high marine survival rates. The degradation of freshwater habitats is only detectable once marine conditions switch back to a low productivity regime and salmon populations are more dependent on high quality freshwater habitat. Consequently, a ratchet effect can develop on population size and stock diversity as climatically-driven conditions in the ocean oscillate between periods of high and low quality (Lawson 1993).

Although within-stock diversity hinders the development of accurate and generalizable long-term forecasts of climate impacts on salmon at watershed scales, policies that protect diverse landscapes and their potential for diverse ecological responses are likely an effective means to hedge bets against future climate changes. Ecosystem and population sensitivity to changes in temperature and precipitation varies substantially across the entire latitudinal gradient that salmon occupy. The ecological and climatic factors that produce intraregional variation in population responses to changing climate (e.g., Hilborn et al. 2003; Crozier and Zabel 2006; Rogers and Schindler 2008) are poorly understood. It is useful to think of salmon landscapes as heterogeneous "filters" of climate. The environmental conditions experienced by any individual population are produced from how the overriding climate signal is expressed in their habitat, as influenced by its geomorphic, hydrologic, and ecological characteristics. We currently have a poor understanding of how landscapes filter climate signals, and how these in turn affect salmon populations. This lack of knowledge is an impediment to developing accurate predictions about the future status of specific salmon populations. However, to some extent, the regional diversity of population responses to climate change appears to derive from local adaptations of salmon populations to heterogeneity in landform and hydrologic conditions (Hilborn et al. 2003; Beechie et al. 2006; Crozier and Zabel 2006; Rogers and Schindler 2008). This response diversity imparts resilience to human social systems, such as fisheries, because they integrate across this ecological heterogeneity (Hilborn et al. 2003). Focusing regional policy on "salmon landscapes" will also be necessary to account for the range of habitats used by salmon over the course of their lives, including migratory corridors (Martin 2006). In the Pacific Northwest, where salmon landscapes are being developed most quickly, such protection of habitat may have to be especially aggressive to counteract ongoing effects of climate change (Ashley 2006).

What science can do to improve salmon-climate policy

Science can play an important role in reducing key uncertainties about climate impacts to which future policy can adapt. Areas that are particularly ripe for study and application to policy include:

- Developing quantitative models that allow projections for temperature, precipitation, and hydrologic conditions to be reliably downscaled to the watershed level. These models will facilitate exploration of the probability that regional conditions will support salmon in specific locations as climate continues to warm (Battin et al. 2007).
- Developing models that allow for integration of multiple factors influencing salmon ecosystems, including the cumulative impacts of climate change, land use, and water use on habitat, fishery harvest, and hatchery effects.
- Exploring the extent to which salmon and co-occurring organisms might adapt to ongoing climate change, thus affecting the direction and magnitude of overall ecosystem response. The role of evolution in ecological responses to anthropogenic change of Earth systems has been essentially ignored in conservation planning (Smith and Bernatchez 2007). This knowledge would inform policy decisions to invest or divest in salmon fisheries, salmon recovery, and hatchery production around the North Pacific.
- Exploring scenarios of future ocean productivity, linkages among ocean and freshwater or terrestrial conditions, and effects of changes in ocean, freshwater, or terrestrial conditions on salmon production at local, regional, and SNPO scales. This knowledge will be important for creating a management regime for cooperative use of the ecosystem services of the SNPO.
- Improving our understanding of how climate change affects the metapopulation processes important to salmon evolutionary and ecological dynamics.
- Refining genetic techniques to identify stocks, and ways to efficiently implement the data generated by those techniques, in harvest management to protect stock diversity in fisheries.

CONCLUSIONS

Predictions of the scope and exact nature of biological responses to future climatic and habitat conditions will always be subject to considerable uncertainty. However, we can be certain that climate will continue to change and biological responses will be heterogeneous across a variety of spatial and temporal scales. We face the challenge of developing management and conservation approaches that are robust to substantial uncertainties about future conditions and capable of responding to change. Simultaneously, we must hone our ability to identify a realistic range of alternative futures. While we have focused on Pacific salmon, the issues we raise are not unique to these species. Many of these same issues will challenge policy to achieve sustained production and conservation of any wide-ranging species as global and regional climate continue to change. ⚓

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