American Fisheries Society Symposium 43:xx–xx, 2004

Natural Climate Insurance for Pacific Northwest Salmon and Salmon Fisheries: Finding Our Way through the Entangled Bank

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Abstract.—This essay focuses on the linkages between climate (variability and change) and sustainable salmon management policies. We show the importance of climate in its effects on salmon production as well as how unpredictable these effects are. Our assessment leads us to conclude that the treatment of environmental uncertainty poses a fundamental conflict between the kind of policies that have been traditionally used in fishery management—basically *command and control* policies that assume predictability and assert engineering solutions to just one or a few aspects of highly complicated problems—and what the environmental variability dictates—policies that embrace environmental variability and uncertainty and acknowledge a lack of predictability for salmon ecosystems. In this regard, we conclude that three things need to happen in order to integrate climate information into sustainable salmon management policies:

1. De-emphasize the role of preseason run-size predictions in management activities.
2. Emphasize preseason and in-season monitoring of both the resource and its environment.
3. Focus on strategies that minimize the importance of uncertain climate variability and change scenarios to increase the resilience of short and long-term planning decisions.

Our bottom line is that sustainable salmon fisheries cannot be engineered with technological fixes and prediction programs, but that climate insurance for Pacific Northwest salmon can be enhanced by restoring and maintaining healthy, complex, and connected freshwater and estuarine habitat and ensuring adequate spawner escapements. If we are interested in purchasing long-term climate insurance for wild salmon so they can better cope with changing ocean conditions, we will likely get the best return on investments aimed at restoring the health and integrity of our beleaguered watersheds. We also believe that the health of northwest salmon resources is inherently dependent upon social, economic, and political pressures in this world of multi-objective resource conflict. Because of the human dimensions of salmon fisheries, we need salmon fisheries if we hope to sustain wild salmon, and vice versa.

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Introduction

Pacific Northwest salmon and salmon fisheries are in crisis. Federal (U.S.) Endangered Species Act listings of wild stocks have caused many regional fisheries to be virtually shut down. In recent years, most of the salmon harvested from California to Washington were spawned in hatcheries. At the same time, the rapid expansion of a global salmon aquaculture industry has drastically reduced market prices for salmon, greatly diminishing the profitability for most salmon fishers. Salmon management policies have, for decades, been focused on achieving better scientific understanding of factors underlying salmon productivity, then using this knowledge to either forecast yield or engineer the fish and their habitats to realize consistent high levels of production. Clearly, these policies have failed to sustain fisheries and to sustain wild salmon populations.

This essay focuses on the role of climate variations in salmon fisheries. We discuss the importance of climate in its effects on salmon production as well as how unpredictable these effects are. Our assessment leads us to conclude that the treatment of environmental uncertainty poses a fundamental conflict between the kind of policies that have been traditionally used in fishery management—*command and control* policies—and what the environmental variability dictates—what Holling and Meffe (1995) call "Golden Rule" policies that acknowledge a lack of control and predictability and aim to facilitate the natural processes thought to provide ecosystem resilience.

To develop our argument, we provide a brief review of state-of-the-art prediction efforts in both salmon fisheries and climate science, discuss recent results from selected studies of environmental impacts on Pacific salmon, describe the nature of human-induced climate change and its potential impact on Pacific Northwest salmon management policies, and relate how salmon have evolved diverse life histories and populations to deal with environmental variability and uncertainty. We conclude the essay by urging a fundamental shift in salmon resource conservation and management efforts that involves new linkages between science, economics, and policy.

Prediction and Salmon Management

For the past few decades, many salmon fishery management agencies have relied on preseason run-size predictions to determine harvest rates and allocations between various user groups. Such forecasts rely on a number of explicit assumptions about salmon population dynamics. For example, in many streams, empirically determined spawner–recruit relationships have been used to set escapement goals at the maximum sustained yield (MSY) population point (see Ricker 1958). Implicit in deterministic stock–recruit concepts like MSY are assumptions that environmental change is (a) relatively unimportant, (b) unpredictable, and/or (c) difficult to translate into the biophysical impacts that ultimately alter the spawner–recruit relationship of interest.

Yet fisheries scientists have long recognized that some of the errors in deterministic (spawner-, cohort-, and/or smolt-based) run-size predictions may be explained by environmental changes, and many have attempted to incorporate environmental data into such *fish prediction* models. For example, in the case of Oregon coho, a number of researchers have developed statistical models correlating various indices of the marine environment with smolt-to-adult return rates (e.g., Nickelson 1986; Lawson 1997; Coronado and Hilborn 1998; Ryding and Skalski 1999; Cole 2000, Hobday and Boehlert 2001; Koslow et al. 2002; Logerwell et al. 2003). There is a growing body of evidence that supports the use of such models, as recent syntheses of field studies in the northeast Pacific Ocean have confirmed strong food-web responses to climate-related changes in nearshore habitat. These biophysical interactions include changes in upper ocean stratification, nutrient concentrations, phytoplankton production, zooplankton production and community structure, forage fish abundance, as well as the distribution of highly migratory pelagics (see Chavez et al. 2002; Mackas and Galbraith 2002; Pearcy 2002; Peterson et al. 2002; and Chavez et al. 2003; for recent perspectives). On the terrestrial side, scientists have long known that temperature and stream flow extremes can have a strong bearing on freshwater productivity for salmonids (e.g., Spence 1995; Bradford and

Irvine 2000). For example, researchers at Washington's Department of Fish and Wildlife have developed empirically based regression models that use stream flow indices as predictors for wild coho smolt production for several index stocks (Seiler et al. 2003).

The whole issue of deterministic prediction is a part of what Holling and Meffe (1995) term "command and control" management. The intent is to define a problem, bound it, and develop a solution for its control. In order to achieve this, policy must be linked to what Holling (1993) calls "first stream" science—essentially a science that assumes that a natural resource system is both knowable and predictable (see Table 1 for a fuller description of this linkage of science and policy).

Climate Prediction

While it is trivial to predict that winter temperatures will be "cold" relative to those in summer in places like the Pacific Northwest, predicting the within and between winter climate variations is much more difficult. In some cases, year-to-year variations on the seasonal rhythms of climate are quite large, though rarely as large as the typical seasonal changes. When poor ocean conditions are blamed for causing problems for salmonids, the target of that blame is never the strong and predictable seasonal climate change but instead it is focused on the unexpected variations superimposed on the regular seasonal rhythms. Since the late 20th century, governments of many nations have invested large efforts in predicting this type of climate variation, with a special focus on predicting season-to-season and year-to-year climate changes (NRC 1996).

Much of the climate prediction effort has been motivated by the promise of societal benefits with an improved forewarning of droughts, floods, or climate-related changes in natural resources like salmonids or other valuable fish stocks. The idea is simple: better predictions of future climate should lead to better predictions and improved stewardship of affected resources. This notion fits very well with some of the annual activities commonly found in fishery management agencies. As noted above, in some regions preseason, run-size forecasts, usually based on the number of parent spawners, smolts, and/or cohort returns, are issued prior to harvest seasons in order to set harvest rates and determine allocations. Errors in preseason, run-size forecasts have been partially attributed to climate and habitat changes, for instance varying ocean conditions and ocean carrying capacity like those described by Pearcy (1992). Thus, better climate predictions offer the promise of reducing some of the preseason run-size forecast errors, at least in cases where the links between climate, environment, and fishery productivity have been quantified.

The state-of-the-art skill in the science of climate prediction rests largely on a demonstrated ability to monitor and predict the status of the tropical El Niño-Southern Oscillation (hereafter simply El Niño). Cane et al. (1986) initiated the modern era of climate forecasting with a bold model-based forecast for an El Niño event in 1986–1987 that was essentially correct. Since 1986, there has been some skill in predicting El Niño at lead times of one to a few seasons into the future. Once an El Niño forecast is made, predictions for climate conditions outside the tropics can easily be made, though forecast accuracy is always imperfect (e.g., Bengston et al. 1993). During the 1990s, there were a few notable successes and a few equally notable prediction failures (see below).

El Niño-based climate predictions are now routinely generated from a variety of sources, ranging from past climate data to the outputs generated with sophisticated computer models. In the early stages of the 1997–1998 El Niño—as early as June 1997—both approaches were used to make remarkably accurate forecasts for the 1998 winter and spring climate of North America (see Barnston et al. 1999 and Mason et al. 1999 for reviews of climate predictions associated with the extremely strong 1997/1998 El Niño event). During El Niño and La Niña periods since 1998, climate predictions for North America were often skillful, though not as spectacularly successful, and in some cases quite inaccurate (for examples, see the NOAA Climate Prediction Center's web page at http://www.cpc.ncep.noaa.gov). *While existing forecast models have shown impressive skill in predicting the onset and demise of recent El Niño events, none have demonstrated great skill in predicting the magnitude and* *reach of tropical El Niño events.* However, the combination of a comprehensive El Niño monitoring system—consisting of real-time buoy, satellite, island, and ship observations—along with the 8–14-month evolution of most events, means that real-time monitoring provides continuous updates on each El Niño event's progress in ways that can be used to minimize forecast errors over the course of each event. The multiseason evolution and sophisticated real-time monitoring system for El Niño allows resource managers to update their expectations for "El Niño impacts" as the event evolves, so early forecast errors can be corrected.

In contrast to the relatively skillful short-term climate predictions described above, climate scientists have demonstrated no skill in climate predictions at lead times longer than 1 year into the future. In spite of this situation, skillful predictions at lead times from a few years to a few decades into the future may be possible if scientists decipher the now mysterious processes that give rise to multi-year climate variations like those associated with the Pacific Decadal Oscillation (PDO) (Mantua and Hare 2002). If this happens, appropriate monitoring systems can be designed and deployed, and the necessary prediction models can be developed (NRC 1998).

An essential point here is that today's best climate forecasts are probabilistic in nature. Unlike the case of deterministic salmon run forecasts, deterministic climate predictions are simply not believed to be possible. To the best of our current knowledge, future climate is subject to highly unpredictable changes because of random events that we simply cannot foresee. Thus, climate forecasts are always presented as changes in the odds for certain events, making climate forecasting akin to riverboat gambling. Playing roulette, success comes with correctly guessing "red" or "black" more often than not. Like playing the colors on a roulette wheel, the science of climate forecasting uses an approach that assigns odds for relatively crude outcomes like "above average temperature" or "near normal precipitation." Long-term forecasts that detail the exact amount of snowfall that a specific ski resort will get in the coming winter are more likely based on someone's wishes than on modern scientific methods.

Climate and Salmon

Because of the never-ending pressures of natural selection, wild animals have evolved behaviors that allow them to "fit" into their seasonally changing habitats. For northwest salmonids, aspects of this evolved behavior include the distinct seasonal runs of various stocks of the same and different species. Thus, the strong seasonal rhythms in the life history of salmonids can more likely be explained as a consequence of evolution in an environment with strong seasonal rhythms than as a result of "climate prediction" by fish.

The results of a study by Logerwell et al. (2003) highlights a few important aspects of the predictability of ocean climate variations thought to be important for Oregon hatchery coho salmon *Oncorhynchus kisutch.* Oregon hatchery coho have a relatively simple life history, at least in comparison to other species and stocks of Pacific salmon. In the Pacific Northwest, most hatchery coho adults spawn during fall or early winter months. After incubation, the eggs hatch into fry that develop as freshwater fish for the next year or so. During their second spring, hatchery juveniles undergo the smolting process at which time they are released from the hatchery and migrate rapidly to sea. Typically, Oregon hatchery coho spend about 18 months at sea before returning to their natal rivers and/or hatcheries to spawn as mature 3 year olds.

There is abundant evidence that Pacific salmon, both of hatchery and natural origins, experience large year-to-year and decade-to-decade changes in productivity. A 30-year database for Oregon hatchery coho shows that smolt-to-adult survival rates in the period 1969–1977 ranged from 3% to 12%, while in the period 1991–1998, those rates were consistently below 1% (see Figure 1). In periods like 1969–1977 and 1984–1991, the year-to-year changes were also large, ranging from ~2% to 6%. The extremely low return rates in the 1990s indicated in Figure 1 were also observed for many other stocks of wild and hatchery salmonids in the northwest. Figure 2 shows observed smolt-to-adult survival rates for five wild and seven hatchery coho stocks tracked by Washington's Department of Fish and Wildlife (Seiler et al. 2003). While there is clearly a large degree of between-stock variability

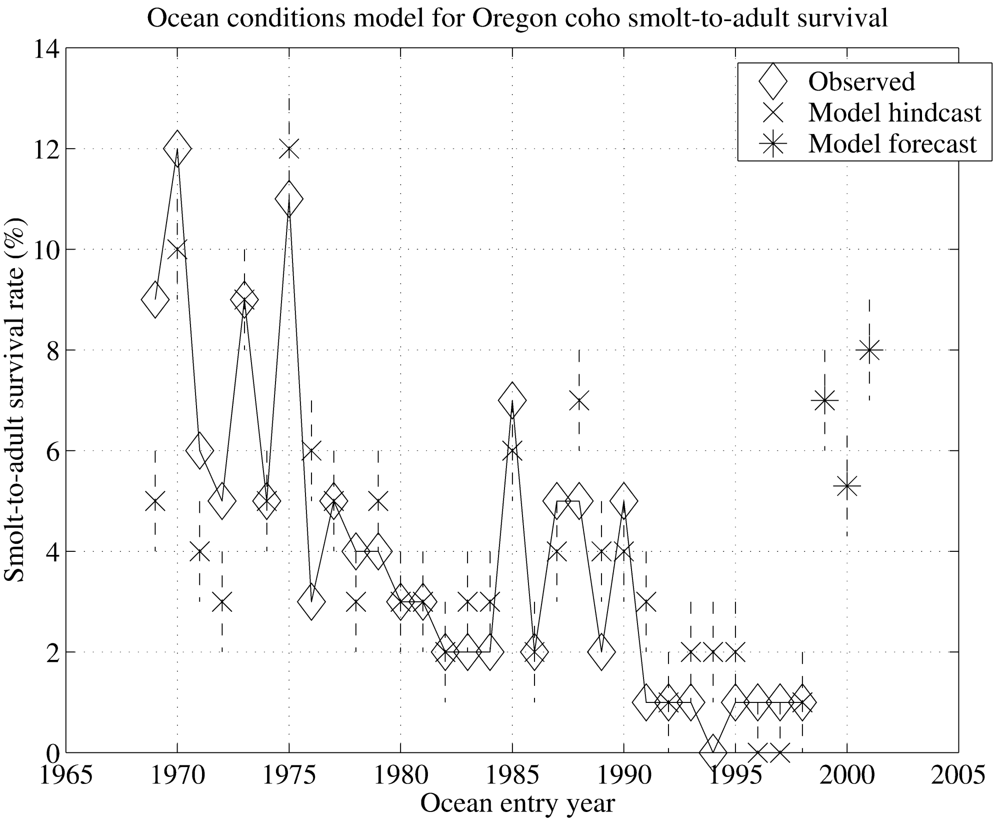

Figure 1. Comparison of modeled and observed Oregon Production Index coho smolt-to-adult survival. This simple environmental model uses observed relationships between smolt-to-adult survival and coastal ocean temperatures, coastal sea level, and winds from 1969 to 1998 to translate subsequent environmental conditions into smolt-to-adult survival rate estimates. Estimates for ocean entry years 1999, 2000, and 2001 indicate improved ocean conditions over those observed between 1989 and 1998. See Logerwell et al. 2003 for more details.

at year-to-year time scales, a common feature in eight of these records is decreasing survival trends from the mid-1980s to the early 1990s and sustained low survival rates for the 1991–1998 period. Hobday and Boehlert (2001) examined smolt-to-adult return records for dozens of coho hatcheries from Vancouver Island to California and the inland waters of the Georgia Strait and Puget Sound. For these regions, they found evidence for regionally coherent very low coho survival rates for 1991–1998 smolt releases. In summary, there is compelling evidence for regionally coherent low smolt-to-adult survival rates, presumably due to inhospitable ocean conditions, for many northwest salmon stocks during this dismal production period.

Logerwell et al. (2003) developed a relatively simple model for using physical environmental data to explain past smolt-to-adult survival rates by synthesizing key results of many earlier studies of coho marine survival and ocean environmental change (e.g., Nickelson 1986; Pearcy 1992; Lawson 1997; Coronado and Hilborn 1998; Ryding and Skalski 1999; Cole 2000; Koslow et al. 2002). The model is based on four environmental indices: (1) the coastal ocean surface temperature in the winter prior to smolt migration; (2) the date of the Spring Transition, the date at which upwelling-favorable winds are initiated; (3) coastal sea-level during the smolts' first spring at sea (a proxy for coastal upwelling and alongshore trans-

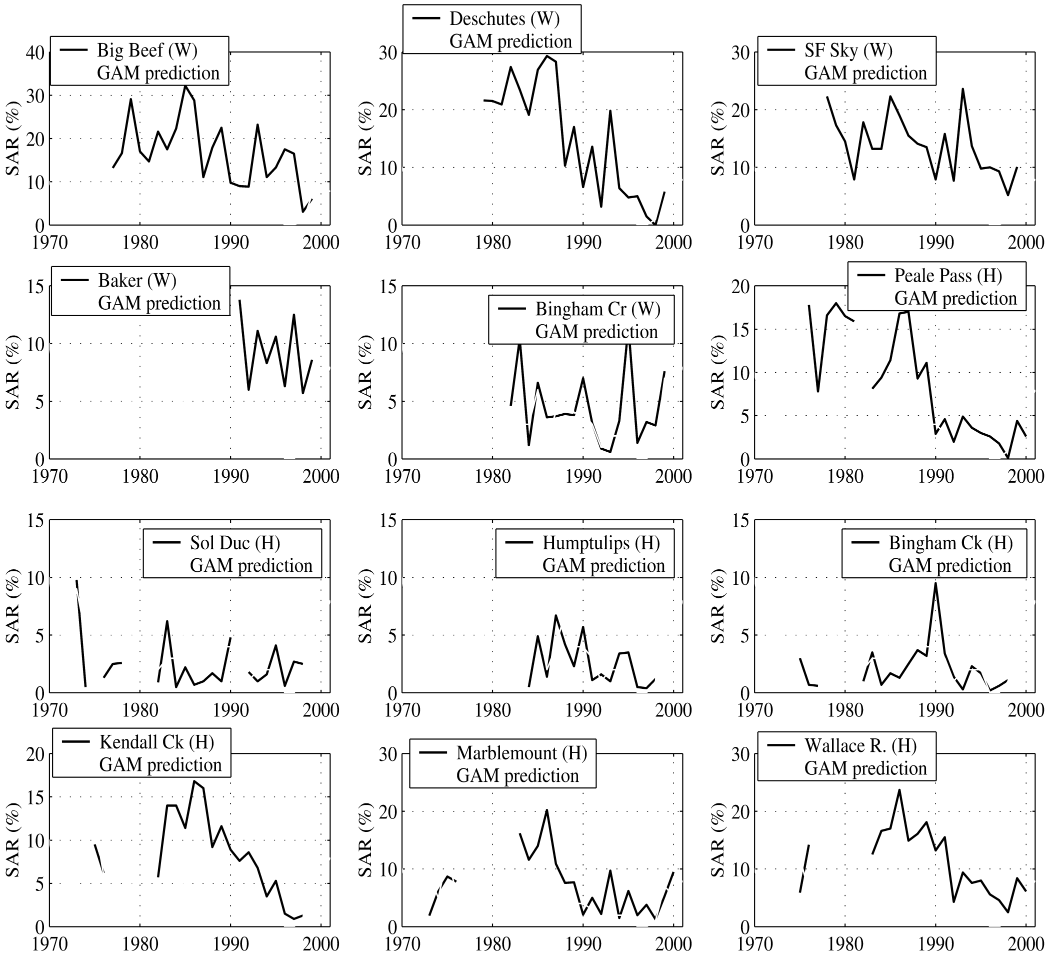

Figure 2. Observed smolt-to-adult survival rates (SARs) for 12 Washington coho stocks (by ocean entry year). Blue lines indicate observed SARs for the stocks listed in each plot, (W) indicates a wild stock, while (H) indicates a hatchery stock. The red lines (labeled GAM) depict the predicted OPI coho survival rates based on Logerwell et al.'s (2003) simple model that includes environmental conditions in the coastal ocean (repeated from Figure 1).

port); and (4) the coastal ocean surface temperature during the maturing coho's first and only winter at sea. Each of the four environmental indices is believed to capture different influences on the quality of the near-surface coastal ocean habitat where juvenile and maturing coho are found. An important finding in this work is that the four different environmental indices are essentially uncorrelated with each other. Yet, considering these four environmental indices in sequence yields an environmental explanation for most of the ups and downs in Oregon hatchery coho smolt-to-adult survival rates for the past three decades.

This model was developed using data from 1969 to 1998 and, with observed environmental data, has provided estimates for smolt-to-adult coho survival for smolts entering the ocean in 1999, 2000, and 2001 (see the *s in Figure 1). Based on this model, coastal ocean conditions were much improved for Oregon coho smolts in 1999, 2000, and 2001, a result that was generally consistent with substantial increases in observed smolt-to-adult coho survival rates. Compared to conditions in 1991–1998, this improvement in smolt-to-adult return rates is believed to be related to food–web changes prompted by significantly cooler wintertime coastal ocean temperatures, an earlier onset of springtime upwelling winds, and more upwelling and stronger equator-ward surface currents in the months of April, May, and June (e.g., see Peterson et al. 2002).

We interpret the results of this modeling work as evidence that the "ocean conditions" important for Oregon coho are the net result of *sequential trajectories of virtually independent climatic processes.* Large-scale climate patterns like El Niño and the PDO are modestly correlated with Oregon's coastal wintertime SST, yet very poorly correlated with the spring transition date and springtime coastal sea levels.

This means that knowing El Niño was underway in the summer and fall of 2002 provided some confidence that coastal ocean temperatures during the subsequent winter (2002/2003) would likely be warmer than average. Yet it provided no clues about how early, how strong, or how often the springtime upwelling winds would blow or what the coastal sea level would be in spring 2003, nor would it provide skill for predicting ocean temperatures in the winter of 2003/2004.

If this biophysical model is valid, predictability for ocean conditions important for Oregon coho is severely limited. Viewed from another perspective, it suggests that Oregon coho face a high degree of environmental uncertainty every year, at least in terms of ocean conditions (but surely also in terms of stream and estuary conditions).

Climate Change and Salmon

There is a growing recognition that, at time frames of a few to many decades into the future, human-caused climate change scenarios may provide useful insights into the potential for protecting and restoring depleted salmon populations. The culprit behind human-caused climate change has been identified: emissions from burning fossil fuels and deforestation have substantially increased the atmospheric concentrations of radiatively important trace gases, the "greenhouse gases." While it is impossible to predict future greenhouse gas emissions, there is little doubt that greenhouse gas concentrations will continue to rise for at least the next few decades and that stabilizing late 21st century greenhouse gas concentrations at levels two or even three times preindustrial levels will require major changes in global energy use patterns and technology (IPCC 2001). The consequences of the human-caused enhancement of Earth's natural greenhouse effect are largely unknown; yet, future climate scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) all point to a high likelihood that climate in the 21st century and beyond will be substantially warmer, and significantly different, than any experienced in the past millennium (IPCC 2001; NAS 2001).

While there has been some speculation about climate change impacts on fisheries, the translation of climate change scenarios into fishery impact scenarios poses a range of difficult problems. An impacts assessment methodology in use today is relatively straightforward. Typically, output is obtained from a climate simulation model; selected climate model outputs are then prescribed for a biophysical response model. For example, Welch et al. (1998a, 1998b) hypothesized that marine habitat for sockeye salmon *Oncorhynchus nerka* and steelhead *O. mykiss* is defined in part by sharp "thermal limits" and that warmer upper ocean temperatures in the late 21st century (around the time of CO_2 doubling) will significantly shrink marine habitat for these species, as well as displace them northward into reduced areas in the Bering and Chukchi seas. Likewise, terrestrial temperature change scenarios from a suite of climate change simulations have been used to estimate changes in stream habitat for salmonids. In one recent study, projected peak stream temperature changes and known freshwater thermal limits for salmonids were used to estimate stream habitat losses in the western continental United States due to global warming (DFW/NRDC 2002).

Even after such methodologies are applied, the translation of climate change information into impacts scenarios carry large uncertainties: in addition to generally poorly known transfer functions and/or parameterizations in the biophysical models, there are dozens of combinations of emissions scenarios and climate models to choose from, with little guidance as to which climate scenarios are most likely to be realized (Mantua and Mote 2002). *An important message for fishery scientists, managers, and policy-makers is the near consensus in the climate research community that the climate of the 20th century is not likely to provide a good guide for climate of* *the near and distant future.* A baseline assumption for us, then, is that environmental uncertainty for Pacific salmon will remain large, if not growing, in the remainder of the 21st century.

Life with Environmental Uncertainty

Many scientists have postulated that a diversity of behaviors and environmental sensitivities serve as evolutionary responses to successful adaptation in uncertain environments (e.g., see ISG 2000). For example, coastal rockfish have evolved a protracted age structure that allows them to weather years of environmental conditions unfavorable to high production. Longevity is their adaptive strategy for perpetuation. Pacific hake have evolved the ability to undertake long seasonal migrations, every year feeding in one large marine ecosystem (Pacific Northwest coastal ocean) and reproducing in another (the Southern California Bight). Western Alaska sockeye salmon have evolved very complex population structures, what Hilborn et al. (2003) call *biocomplexity,* to maintain their resilience to environmental variability and change.

At the metapopulation level, each species of Pacific salmon exhibits many such risk-spreading behaviors through a broad diversity of time-space habitat use by different stocks and substocks of the same species. Lichatowich (1999) put it this way: "life history diversity is the salmon's response to the old adage of not putting all one's eggs in the same basket." In the words of Hilborn et al. "biocomplexity of fish [western Alaska sockeye salmon] stocks is critical for maintaining their resilience to environmental change."

Empirical evidence for diverse life history behaviors and habitat use by salmonids, and their close relationship to the physical environment, is found nearly everywhere researchers have looked. For instance, studies of natural coho smolt production in western Washington yield evidence for a wide variety of stream flow sensitivities in nearby watersheds (Seiler et al. 2003). In some systems, wild coho smolt production is limited by high winter flows that scour nests and damage incubating eggs. In other streams, the main limiting factor is low summer flows that reduce rearing habitat. In other streams, high fall flows allow spawners to access otherwise unreachable tributary spawning beds. Seasonal climate and short-term (day-to-day) weather variations cause these limiting flow factors to vary sometimes within and sometimes between streams from year-to-year as well. The bottom line is that the complex landscape and variety of watersheds in western Washington provide a diversity of habitats with different environmental sensitivities. Because coho salmon occupy each of the different habitats, the species as a whole carries a diverse portfolio of climate and environmental sensitivity, what we like to think of as an evolved expression of *natural climate insurance.*

Recent studies have attempted to better understand the temporal and spatial characteristics of marine salmon habitat as well. Weitkamp and Neely (2002) document the fact that different coho stocks utilize distinctly different areas in the coastal waters of the northeast Pacific. Mueter et al. (2002) demonstrate that year-to-year coastal SST and upwelling wind variations covary at spatial scales of just a few hundred kilometers in spring, summer, and fall, but at much larger spatial scales (1,000–2,500 km) in winter. Taken together, these studies suggest that different stocks of the same species (in this case, coho) also experience a diversity of marine habitat at the same time in different places, and at different times in the same places. Just like the case of freshwater habitat uncertainty and complexity, prominent characteristics of marine habitat for salmon are diversity, variability, and unpredictable changes at a broad spectrum of time and space scales.

Given the complexity of freshwater salmon habitat in western North America and marine habitat in the Pacific Ocean, it seems likely that these examples of complex habitat, variability, environmental sensitivity, and complex salmon stock structure are not unique to western Washington coho or western Alaska sockeye salmon. Instead, biocomplexity in wild Pacific salmon populations appears to be more likely the rule than the exception.

What Does It All Mean for Salmon Policy?

How might an explicit consideration of climate and environmental uncertainty aid salmon management efforts? We first review some key characteristics of the inseparable linkages between science and natural resource policy, and then show that, in our view, the issue of saving wild salmon is inseparably linked to the issue of saving salmon fisheries. Finally, we offer some specific recommendations of what might be done to resolve some existing climate-related conflicts between salmon ecology and salmon management.

Although at times they may seem independent, in our view, natural resource science and policy are inextricably linked. In fact, this is essential if policy is to be based on scientific assessments and analyses. Holling and Meffe (1995) and Holling (1993) characterize two distinct forms of this linkage, which we summarize in Table 1. The first links "command and control" management with "first stream" science. The key underlying assumptions of both are that relevant aspects of the natural resource system are knowable and predictable and that variability can be controlled. Examples of this are salmon policies that try to maintain a constant absolute harvest or constant escapement, or use hatcheries to boost fishery production at times of low natural production. The second links "golden rule" management with "second stream" science. The assumption here is that relevant aspects of the system are inherently unknowable and unpredictable and that variability is to be celebrated and preserved. The golden rule management goal is to facilitate existing natural processes rather than control them. For example, to maintain and restore diverse and connected freshwater and estuarine habitat, to restrict harvest rates to very low levels to allow as wide a diversity of populations to attain adequate spawning escapement, and to time hatchery releases to have minimal direct interactions with wild populations are all examples of golden rule management.

It is our contention that sustainable wild salmon populations and sustainable salmon fisheries are tightly linked. In our view, one necessary element for sustainable salmon fisheries is sustainable wild salmon populations. While salmon hatcheries now support the bulk of salmon harvests in the Pacific Northwest, history tells us that hatchery production of salmonids is not a sustainable fishery policy (Lichatowich 1999; Taylor 1999). From an ecological perspective, the genetic and behavioral diversity found in wild salmon populations and absent in most hatchery populations may be critical for the long-term survival of salmon in the face of environmental change (Hilborn et al. 2003). To sustain wild salmon in our world of natural resource conflict is to sustain the direct interaction between humans and salmon. For example, in the 1950s, hydropower interests lobbied for the construction of Moran Dam, which would have risen 220 m from the bottom of the Fraser River Canyon and blocked access to 44% of the upriver sockeye spawning grounds. This proposal created a Columbia River-style tradeoff between the choice of industrial development over wild salmon habitat and productivity. Fishing interests led fierce political opposition that eventually halted this project (Meggs 1991). Without viable fisheries, many Pacific Northwest salmon stocks would likely have gone extinct long ago. Fisheries generate the social and economic incentives that build the political clout needed to preserve the source of their sustenance.

With these management considerations in mind, what should we do? It seems to us that people now know enough about salmon ecology to provide a list of needs for policy makers to develop effective action plans to save threatened wild salmon populations. Key pieces of an effective restoration plan should include the following (ISG 2000):

- Restrict harvests so adequate numbers of adults can spawn, and avoid harvest policies that might alter the life history and/or genetic diversity of the spawning population.
- Restore diversity by reforming and/or closing hatcheries to significantly reduce negative impacts on wild stocks.
- Restore and protect habitat, and where necessary, remove barriers to fish passage.
- Align economic incentives for salmon fisheries with conservation incentives for preserving wild salmon populations.
- Accept variability, environmental uncertainty, and acknowledge a lack of predictability (cf. ISG 2000).

In contrast, current efforts to sustain salmon fisheries are clearly a matter of often poorly coordinated politics, economics, law, and ecology. As wild salmon numbers have declined, a combination of scientific, political, and socioeconomic pressures have led to a slow withering of harvest opportunities, an increased dependence on hatchery production, and seasons that are ratcheted down to smaller and smaller windows of time to protect endangered wild stocks while still allowing for harvest opportunities. Policies have generally focused on single-species biomass or numbers of salmon (e.g., OPI hatchery coho for harvest), rather than considering the ecosystems of which the target fish populations are a part. Salmon restoration efforts have concentrated on tweaking the status quo, and this has been especially true with efforts to improve fish passage around dams and to reform hatcheries. Management agencies have attempted to reduce and/or eliminate variability by using salmon hatcheries to divorce fish production from habitat. Globalized economics have forced harvested wild salmon to be sucked into an international commodity market that is flooded with very low-price, high volumes of aquaculture salmon, a market reality that most Pacific Northwest salmon fishers are struggling to compete in. Wild salmon markets must be restructured if they are to survive, perhaps in ways that focus on relatively low volumes of high-valued premium quality fish for domestic and foreign consumption. Such specialty markets are already developing with brand names such as "Copper River Sockeye" and "Yukon River Kings." Finally, deterministic and static concepts like maximum sustained yield have been used to set harvest goals, pressuring fishery managers to develop better predictive models so harvests can be maximized while still offering protection for spawning stocks, a scenario under which many wild populations exhibit chronically low production (Knudsen 2000).

In summary, we have seen scientific management that forces complex and highly variable biophysical systems to be balanced on a razor's edge to satisfy social demands for both *extraction and protection* of the same resource along with alternative uses for critical habitat. As a result, we have developed conflicts between those who want to sustain wild salmon populations and those who want to sustain salmon fisheries. Clearly, this has become a "lose–lose" situation.

From this comparison, the main climate component of the conflict between protecting and restoring wild salmon populations and protecting salmon fisheries lies in the treatment of environmental variability, and it is in this realm where the potential for policy reform looks greatest. While socioeconomic pressures produce political pressures to reduce variability and/or increase predictability so that resource use can be maximized, salmon habitat and ecosystems contain fundamentally unpredictable dynamics (cf. Holling and Meffe 1995) (Table 1). Climate enters this picture through its role in providing strong limitations on ecosystem predictability, a situation that is not likely to change in the future.

Table 1. Key characteristics of linkages between science and natural resource policy, after Holling and Meffe (1995).

	First stream	Second stream
Science	• System knowable and predictable	• Ecosystem evolving, has inherent unknowability and unpredictability
	• Science of parts and disciplines	• Science of integration
	• Seek prediction	• Seek understanding
	Command and control	Golden rule
Policy	• Problem perceived, bounded, and solution for control developed	• Retain or restore critical types and ranges of natural variations
	• Objective: reduce variability and make system more predictable	• Facilitate existing processes and variability

So how might we better manage our salmon resources if changes in climate, ocean conditions, and salmon populations are so difficult to predict? We have three suggestions:

- De-emphasize preseason run-size predictions.
- Emphasize monitoring, including in-season run-size assessments to guide short-term harvest decisions and the development of appropriate real-time environmental measurement systems to gain insights into environmental impacts on stock productivity.
- Focus on strategies that minimize the importance of uncertain climate variability and change scenarios.

Now consider these suggestions one at a time. First, if predicting the future presents such a difficult challenge, it would be wise to distance management performance from prediction accuracy. For year-to-year management needs, monitoring target stocks and their habitat offers a much more fail-safe approach than does a continued reliance on highly uncertain predictions. Simple environmental models like the one used to estimate coho smolt-to-adult survival provide one means for translating the products of environmental monitoring into an estimate for difficult to measure coho survival rates. An even better approach would rest on directly monitoring the target stocks, a daunting task, yet one that has received considerable attention in recent research projects along the Pacific Coast. If social and political pressures demand preseason predictions, such monitoring-based "forecasts" (using any combination of cohort, smolt, or environmental models) should explicitly acknowledge the large uncertainties that exist. Thus, when preseason run-size forecasts are made, stakeholders and managers should be presented with a range of possible populations to work with, along with some estimate for the odds of actually witnessing the high, low, and middle parts of the predicted range. Alaska's Department of Fish and Game manages Bristol Bay sockeye salmon fisheries in precisely this way, annually developing preseason run-size forecasts with explicit (and often large) uncertainties, along with in-season run-size monitoring and real-time terminal-area harvest decisions to ensure escapement goals are met. On the other hand, in California, Oregon, and Washington, where many wild salmon populations are severely depleted, harvest managers rely on deterministic and scientifically questionable preseason run-size forecasts, difficult to verify assumptions about at-sea distributions of many wild and hatchery stocks, and mixed-stock ocean fisheries (SRSRP 2001). It is clear that Alaska's emphasis on monitoring rather than deterministic predictions has contributed to the sustainability of Alaska's wild sockeye salmon fisheries. We believe the Alaska approach provides an attractive alternative to the northwest salmon management's continued reliance on deterministic preseason run-size forecasts.

A second critical step is to do enough monitoring so that changes in freshwater and marine productivity can be tracked and discriminated. Today, only a small number of streams are monitored for the full life cycle of salmonids (e.g., see Seiler et al. 2003). Keeping track of adult spawners and estimating harvests allows for a gross estimate of productivity. Because marine variability has strong influences on salmon productivity, it is critically important that harvest rates be reduced in periods of low ocean productivity to allow for adequate spawner escapements (Knudsen 2002). A better understanding of changes in marine and freshwater productivity rests on the establishment of long-term, continuous records of the age-structure of spawners, parr, and smolt production, in addition to the more commonly collected index counts used to estimate total spawners. A better understanding for existing bottlenecks in wild salmon productivity is also necessary to maximize the "bang for each buck" spent on salmon restoration projects. We realize that monitoring programs are expensive and difficult to maintain. However, we suggest that at least as much money and effort should be spent on monitoring as is already spent on artificial enhancement and short-term engineering fixes (i.e., salmon hatcheries).

Finally, for dealing with the uncertainties posed by natural climate variability as well as long-term anthropogenic climate change, the most conservative and effective long-term strategy is one that minimizes the importance of highly uncertain climate change scenarios and their attendant impact scenarios for wild salmon. In this realm, the critical step is to place a much higher priority on restoring the natural climate insurance that wild salmon populations must have evolved to survive and thrive in the face of past environmental changes. We believe that this insurance is intimately associated with a diversity of life history behaviors that, in turn, are directly linked to the availability of healthy, complex, and connected freshwater habitat. A diversity of freshwater habitat leads to a wide range of seasonal runoff patterns, as well as a wide range of short-term runoff responses to short-term weather and geologic events. Such environmental variability effectively forces substocks of the same species into different niches and different behaviors through the never-ending process of natural selection. If we are interested in purchasing long-term climate insurance for wild salmon so they can better cope with changing ocean conditions, we will likely get the best return on investments aimed at restoring the health and integrity of our beleaguered watersheds. If we do this effectively, we might also bring back the resource base required for viable and sustainable salmon fisheries.

Acknowledgments

While this essay was inspired by a variety of insightful commentary on the Pacific Northwest salmon crisis, Jim Lichatowich's *Salmon Without Rivers,* Joeseph Taylor's *Making Salmon,* and Arthur McEvoy's *The Fisherman's Problem* were especially provocative books that prompted us to consider the broader aspects of salmon fisheries than those related to the biophysical interactions of climate, environment, and salmon. Taylor's (2001) unpublished essay "Seeking the Entangled Bank: Ecologically and Economically Sustainable Salmon Recovery" pushed us to further grapple with the human side of the northwest salmon equation. We thank Ed Miles, Amy Snover, Bill Pearcy, and three anonymous reviewers for their constructive comments on draft versions of this essay. This essay was supported by collaborations in the University of Washington's Climate Impacts Group, an interdisciplinary effort within the Joint Institute for the Study of the Atmosphere and Oceans and School of Marine Affairs and was funded under NOAA's cooperative agreement #NAI17RJ1232 and The Hayes Center. This is JISAO contribution #884.

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