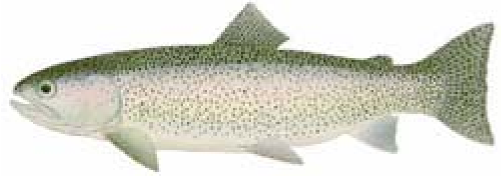
Phase II-Salmon Recovery Planning
Strategic Research Plan

Working Draft
(To be Revised January 2006)



Northwest Fisheries Science Center
National Oceanic and Atmospheric Administration
2725 Montlake Blvd E.
Seattle, WA 98112

July, 2005

PREFACE

The Phase II-Salmon Recovery Planning Strategic Research Plan was developed to identify how research questions arising under salmon recovery could best be addressed through collaborative, inter-Divisional research at the Northwest Fisheries Science Center (NWFSC). Multiple authors drafted the plan after group discussions among scientists from Divisions conducting salmon research at the NWFSC. A few gaps in the plan remain, and it was determined by NWFSC staff in the spring of 2005 that finalizing the Phase II plan would best be completed after (1) the newly-forming Research Planning Team identified their objectives and tasks, and (2) the new Puget Sound ecosystem-based management initiative completed its first guidance document. The Puget Sound ecosystem-based management initiative was started following completion of the regional draft recovery plan for ESA-listed Chinook in Puget Sound. This major accomplishment highlighted that the implementation of the recovery plan for Chinook must be considered in the full context of the Puget Sound ecosystem. The Puget Sound ecosystem-based management initiative will define the broad overarching research needs into which a Phase II Salmon Recovery Planning Research Plan must fit. This initiative necessitates that Phase II plan be re-visited and revised with guidance from the initiative.

The Research Planning Team has been convened, and is identifying the scope of its first few years' work, and how existing research plans will be revised and adapted over time. The effort to develop a collaboratively defined document describing the Puget Sound ecosystem and the major science needs to help move management of Puget Sound natural resources towards ecosystem-based management also is proceeding. The final, broadly agreed upon Puget Sound ecosystem document will be completed by the end of December 2005. Early in 2006, with guidance from the Research Planning Team and the content of the Puget Sound ecosystem document, the Phase II Salmon Recovery Planning Research Plan will be completed and implemented. The "lessons learned" from Puget Sound will have direct application to the other recovery domains for ESA-listed Pacific salmon.

INTRODUCTION

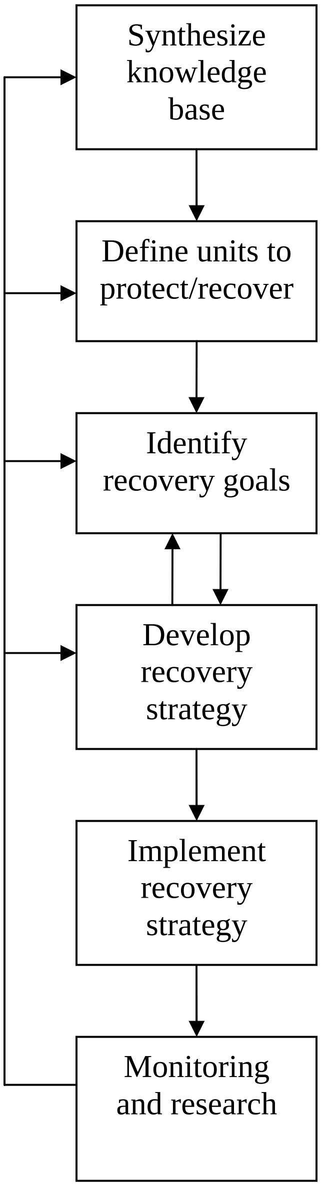
The primary goal of salmon recovery planning is to describe a set of actions in habitat, hatchery, hydropower, and harvest management that will result in recovery of listed salmon ESUs. The NWFSC has conceptually divided recovery planning into two phases. Phase I identifies population- and ESU-viability criteria based on 4 key population characteristics that affect persistence: abundance, productivity, spatial structure and diversity (i.e., the Viable Salmonid Population parameters, or VSP; McElhany et al. 2000). The technical task of establishing viability criteria in Phase I is accompanied by policy determinations of what constitutes an acceptable risk to the ESU. Combined, the viability criteria and determination of acceptable risk constitute population and ESU recovery goals. Phase II identifies suites of actions that are likely to achieve population and ESU recovery goals, based on analysis of multiple factors that might constrain or encourage recovery (Beechie et al. 2003). Individual Technical Recovery Teams (TRTs) have developed, or are in the process of developing, viability criteria for specific ESUs (http://www.nwfsc.noaa.gov/trt/index.html). TRTs and local planning groups have begun the process of Phase II recovery planning.

Phase II planning is infused with questions that span the science-policy interface, including:

- What constitutes ‘sufficient’ technical content and certainty in outcomes of population-scale recovery plans?
- What are “acceptable” risk levels for ESUs? How do they vary with economic or social costs?
- To what extent are potential hatchery, harvest and habitat management actions constrained by non-biological factors?
- What combination of natural-origin and hatchery-origin salmon constitutes an ‘acceptable’ risk of ESU extinction?
- Which alternatives for a biologically “recovered” ESU are consistent with policy objectives?
- Since the design and intensity of a monitoring plan affects the likely time to de-listing or the uncertainty and risk inherent in a de-listing decision, what types of monitoring program will fill policy needs?

Such questions have both science and policy components, and understanding the respective roles of science and policy is crucial to successful recovery planning. For the purposes of this research plan, we illustrate the roles of science and policy using a simple adaptive management protocol modified from Stanford and Poole (1996) (**Figure 1**). The protocol suggests that the role of science is strongest early in process, focusing on synthesizing current scientific knowledge, defining the units of biological diversity to protect, and setting recovery goals. Science and policy interact more strongly in developing the recovery strategy. Science objectively assesses the likely biological outcome of potential actions, and policy informs their socioeconomic feasibility. Subsequent monitoring and research inform both science and policy through iterative information feedbacks that refine the knowledge base and help adapt the strategy to new information.

Figure 1. Adaptive management protocol illustrating steps in developing and implementing a recovery strategy, and monitoring feedback loops that help refine recovery actions over time (adapted from Stanford and Poole 1996). Examples of how science and policy contribute to each step in recovery planning for Pacific salmonids are shown at right.



e.g., define elements of population and ESU status (McElhany et al. 2000), habitat-forming processes and functions of habitat (Beechie et al. 2003), hatchery, harvest refs.

e.g., identify ESUs (see *Status Reviews*), historical population structure and major diversity groups within ESUs (Ruckelshaus et al. 2001, McElhany et al. 2003, McClure et al. 2003, Lawson et al. 2004).

e.g., develop population and ESU viability criteria (see http://www.nwfsc.noaa.gov/trt/index.html). Policy input on acceptable risk levels.

e.g., from knowledge base synthesized in first step, identify major factors potentially limiting recovery, a strategy to address them, and the likely effects of alternative actions on VSP (see Scott et al. 2003, TRT case studies, others). Policy input on feasibility of alternative strategies.

e.g., policy input on timing, number and types of projects implemented; depending on budget, political and social support, opportunities.

e.g., provide technical guidance on developing monitoring strategy (refs); policy guidance on magnitude of effort based on budget, tolerance for uncertainty.

To improve the contribution of science to Phase II recovery planning, our research plan is focused on two main purposes. The first purpose is to improve our ability to predict the biological outcome of potential recovery actions, which primarily contributes to developing the recovery strategy. The second purpose of our research is to improve the use of science in adaptive management frameworks. This science is a key to evaluating scientifically sound recovery strategies and providing objective, empirical information for improving the choice of recovery actions through adaptive management feedbacks. With these purposes in mind, we first present an overview of our research approach. We then outline a series of research questions that address each component and its linkage in the conceptual framework. Finally, we conclude with a brief description of how we envision this document evolving over time as questions are answered and new issues arise.

Research Approach

Our research is organized according to a simple conceptual model of linkages between management actions and the viability of salmon populations and ESUs. In this model, population and metapopulation dynamics integrate the combined effects of potential management actions spanning all life stages of the salmon (**Figure 2**). Each class of management actions contains its own idiosyncratic suite of pathways and mechanisms that affect salmon fitness, but all are linked through salmon population dynamics. Based on this conceptual model and the adaptive management protocol illustrated in Figure 1, we identify three general research themes: (1) population and metapopulation dynamics, (2) mechanisms linking management actions to population dynamics, and (3) conducting science within the context of adaptive decision making frameworks. The first two themes are driven primarily by the need to better predict the biological outcome of potential recovery actions, and span biological scales from individual fish to populations and ESUs. Hence questions within this theme are mainly scientific, with little cross-over into policy issues (**Table 1**). The third theme directly addresses issues at the science-policy interface, focusing on producing scientific results illustrating how alternative futures can inform choices of actions, integrating biology and economics in recovery planning, and in developing monitoring requirements for effective adaptive management.

We recognize that these research themes span many scientific disciplines, require scientific inquiry at a wide range of spatial and temporal scales, and encompass both short-term and long-term research programs. Within each theme we identify a series of overarching questions, the scope of which often exceeds the capabilities of individual divisions or organizations. Therefore, collaboration across programs and divisions within the NWFSC, as well as with other agencies and institutions, will be essential to advancing our scientific knowledge. Accomplishing our objectives will also require research that ranges from correlational studies encompassing hundreds of thousands of square kilometers of land or ocean, to laboratory studies examining genetic and biological mechanisms that alter salmon fitness. Where appropriate, field studies may be focused in specific focal watersheds, but with the intent that study results have general application to many populations or ESUs. We recognize that some important questions will involve long-term data collection, modeling and analyses—the results from which may not be available to inform decisions needed in some near-term planning efforts. Such long-term research projects are critical to successful salmon recovery, as they contribute to improved implementation of recovery actions through adaptive management feedback loops.

Figure 2. Conceptual model depicting biological linkages used in guiding research efforts for Phase II salmon recovery planning.

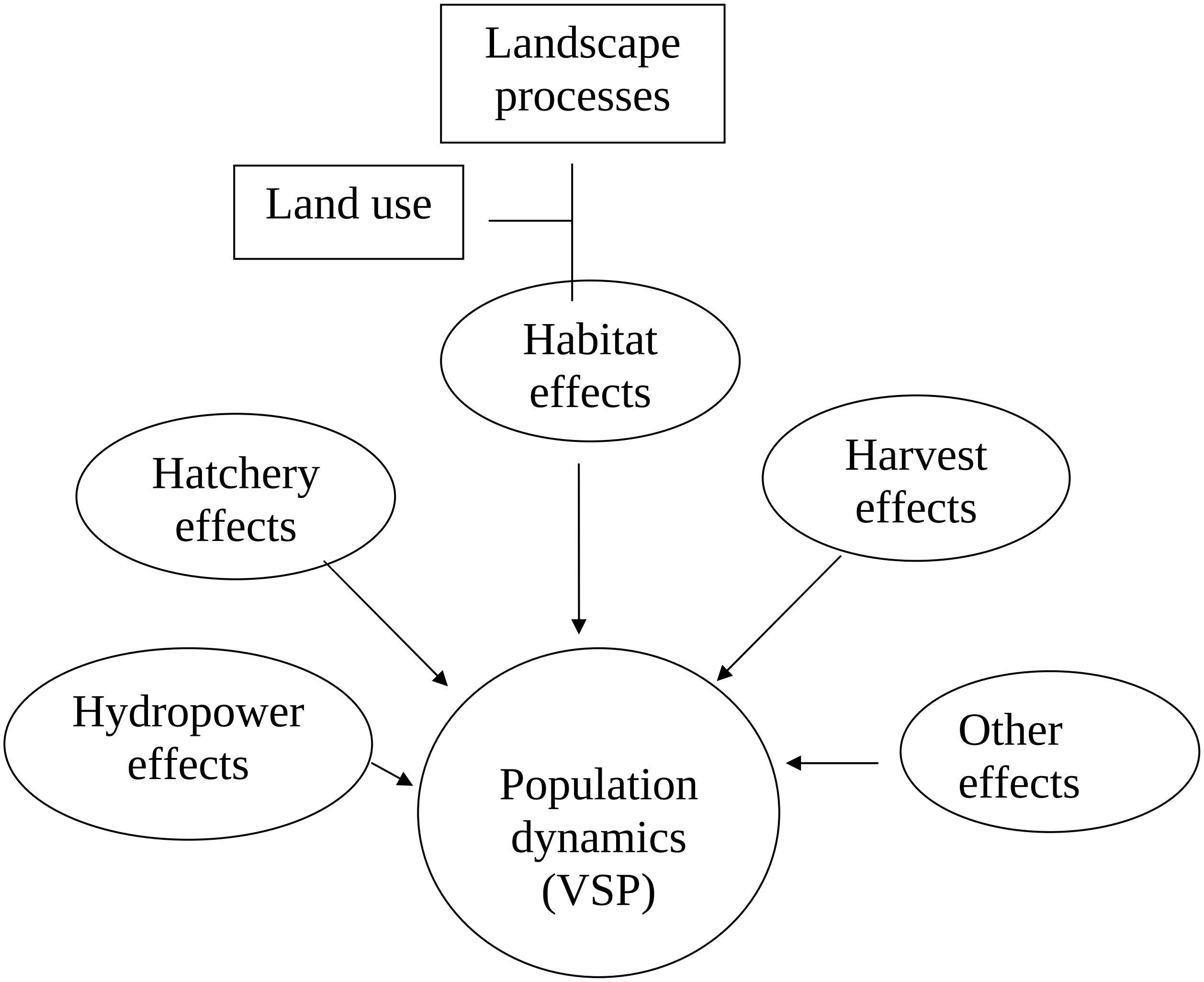


Table 1. Key research questions for Phase II salmon recovery planning.

I. Population/metapopulation dynamics

1. What are the cumulative, integrative effects of habitat, hydropower, harvest and hatchery management practices, ecological interactions, and other environmental conditions on the VSP characteristics of a population?
2. What are the cumulative, integrative effects of recovery actions on ESU viability?

II. Mechanisms

1. What are the direct and indirect effects of physical, biological and chemical characteristics of freshwater, estuarine and marine habitats on the VSP characteristics of a population?
4. What are the direct and indirect effects of alternative hydropower management activities on the VSP characteristics of a population?
5. What are the direct and indirect effects of alternative harvest management activities on the VSP characteristics of a population?
6. What are the direct and indirect effects of alternative hatchery management activities on the VSP characteristics of a population?
7. What are the effects of ecological interactions (e.g., disease, competition, predation) and/or ecosystem characteristics on the VSP characteristics of a population?
8. How is the biology of individuals (e.g., physiology) linked to fish condition and salmon population VSP characteristics?

III. Science in a decision framework

9. How does incorporating uncertainty about future environmental conditions into scenarios assessing the cumulative effects of recovery actions on the VSP characteristics of a population affect predictions of salmon population response?
10. What monitoring is necessary to detect population and ESU status and the effects of recovery actions on the VSP characteristics of a population?
11. How does integrating biological and economic information in an evaluation of the effect of suites of recovery actions on the VSP characteristics of a population or ESU alter the prioritization of impacts?

Key scientific questions for Phase II salmon recovery planning

The first set of questions (population and metapopulation dynamics, Table 1) is aimed at addressing the overall task of Phase II recovery planning, which is to estimate the potential effects of management actions and natural environmental variability on the status of salmon populations and ESUs. The focus of these 2 questions is largely synthetic. That is, they involve integrating the estimated effects of many factors and then exploring their impacts on population and metapopulation dynamics. At the core of the first question is a salmon life-cycle view that links life stage-specific survivals in a population-dynamic framework. These links can be quantitative or qualitative, depending on the availability of information for each species and potential factor(s) affecting its status. The second research question asks how the collective VSP attributes of populations within an ESU affect its persistence. Estimates of individual population status resulting from the cumulative effects of recovery actions can be used to assess how the distribution of population risks across the ESU is likely to affect long-term persistence of fish in the ESU. Metapopulation theory provides a useful framework for addressing this question, which focuses research efforts on understanding how inter-population dispersal, extinction-colonization dynamics, and the distribution of salmon diversity across the group of populations combine to affect metapopulation (i.e., ESU) persistence. Research under these questions will also address key uncertainties in these models, focusing on identifying critical data needs for better predicting salmon population or ESU responses to recovery actions.

The second group of questions (mechanisms linking management actions to population or metapopulation dynamics, Table 1) explores the effects of individual types of recovery actions on VSP characteristics. In order to understand how recovery actions might affect population or ESU persistence, the effects of natural variability in condition and functioning of habitat on salmon populations must first be understood (question #3). The human-caused effects of habitat changes, and harvest, hatchery and hydropower management on VSP then need to be evaluated to understand the likely effects of individual management actions on population or ESU recovery (questions #3-8). In general, the questions in this group strive to address 2 key questions that will help identify recovery strategies: (1) what are the predicted effects of each factor on population status (i.e.,VSP)? And (2) what are the likely mechanisms through which each factor affects VSP? Understanding the mechanistic links between habitat characteristics, hatchery, harvest or hydropower operations and VSP can involve understanding how fish condition and physiology are affected by such factors, and in turn how the biology of individual fish affects overall population parameters.

The final set of questions is aimed at exploring how scientific results can best be used to inform recovery management decisions. Exploring alternative future scenarios is a useful way to illustrate for decision-makers how fish populations might respond to different sets of recovery actions, and to help them make decisions in the face of uncertainty associated with making future projections of salmon population status (question #9). Designing monitoring plans that will inform future adjustments to recovery actions (question #10) and incorporating economic and biological criteria into analyses of action effects (question #11) are essential contributions from science to recovery planning efforts.

SPECIFIC SCIENTIFIC QUESTIONS TO BE ADDRESSED IN PHASE II SALMON RECOVERY RESEARCH

The specific research questions we identify for guiding salmon recovery planning research are grouped into 3 categories: (1) research addressing the effects of recovery actions on overall salmon population and metapopulation dynamics, (2) questions aimed at identifying mechanisms through which habitat, hatchery, hydropower, harvest and other environmental factors affect population status, and (3) questions pertaining to the science of incorporating biological, social and economic information into recovery planning decisions.

I. POPULATION/METAPOPULATION DYNAMICS

1. What are the cumulative, integrative effects of habitat, hydropower, harvest and hatchery management practices, ecological interactions, and other environmental conditions on the VSP characteristics of a population?

Background

The basic salmon life cycle model described in the Introduction provides an organizing framework for defining key research questions regarding the integrative effects of conditions and impacts across the full life cycle of a salmonid population. The framework is generally structured around life stages associated with major habitats - spawning and juvenile rearing in freshwater, transition though the estuary and early ocean phase, the adult ocean phase, and upstream migration to spawn. Salmonids are generally characterized by a strong adult homing response - adults typically returning to their natal tributary streams for spawning. Within that basic pattern, salmonid ESUs and their component populations exhibit many variations in life history patterns - the temporal and spatial distribution during freshwater, estuarine and ocean rearing phases.

Policy Implications

The general approach to recovery planning for listed Pacific Salmonid ESUs recognizes populations as the fundamental units of production within an ESU. Developing and implementing successful recovery strategies will depend upon relatively accurate assessments across the landscape used by particular populations. . In the past, limiting factors assessments have been done on a regional level or from the general perspective of an ESU. Improving our knowledge of habitat/fish productivity relationships and across the landscape used by particular population units will promote the efficient use of recovery and restoration resources.

Current Understanding

Salmon populations are generally classified into one of two basic life history patterns based on their predominate life history pattern: Stream type populations – most juveniles reside in freshwater for one or more years, or Ocean type - juveniles migrate to the ocean during their first year of life (Healy (1991). Individual populations can exhibit a great deal of variation on the basic themes. Components of the juveniles produced from a particular spawning reach may disperse and rear in a range of habitats in addition to the natal reach. Alternative rearing locations may by used for over-wintering. Diversity in terms of life history patterns is hypothesized to be an important hedge against the short and long term environmental variability (McElhany et al. 2000). Stream type and ocean type salmonid populations utilize freshwater habitats, marine habitats and transition areas (estuaries, nearshore ocean waters, lower mainstems of major rivers). Viable populations require access to and connectivity among habitats of sufficient quantity and quality to sustain population growth rates and abundance.

In the generalized life cycle model, the effect of conditions and actions on salmonid populations can be expressed in terms of three sets of input parameters: survival rates between life history stages, capacity or abundance at a particular life stage, and alterations or variations in population structure (maturation rates by age, fecundity, etc.). Incorporation of some impacts is relatively straightforward, other impacts or elements are more difficult to characterize. For example, estimates of exploitation rates are estimated many populations or population groups for use in harvest management. These rates can usually be directly incorporated into a simple life cycle model. The effects of abundance driven harvest regimes are harder to incorporate, but analyses of these options can be carried out using Monte Carlo modeling approaches or scenario analyses.

Detailed knowledge of absolute survival rates at different stages among habitats is rarely available for salmonid populations. Cumulative survival estimates – in the form of spawner to spawner ratios, population growth rates are more generally available or can be inferred from representative data sets. In some cases, direct estimates or indices of survival between major life history stages can be generated (e.g., Petrosky et al, Achord & Zabel, McClure et al, 2003). Typically these cumulative survival estimates cover major segments of the life history pattern often extending over significant temporal and spatial scales. For example, smolt sampling at weirs or mainstem dams provide for estimates of egg or parr to smolt survival estimates. Smolt to adult return rates (SARs) are also available for several populations or population aggregates.

Egg to smolt survival estimates for stream type fish exhibit substantial annual variation – average estimates typically range from 4 to 15 percent. While estimates of the allocation of mortalities across space and time within egg-smolt phase are generally not available, experiments and monitoring efforts have identified significant levels of mortality in at least three substages: incubation/early rearing; summer rearing and overwintering. (e.g., Kruzic, et al. 2001, Cunjak, 1996, steelhead ref) Patterns of dispersal among habitats relative to these life history stages are not well understood for most populations.

Diversity and spatial structure are important considerations in evaluating population viability. Given the current state of knowledge regarding relationships between habitat conditions and survival rates, population level responses and variations in future conditions, it is not feasible to use detailed modeling assessments to directly assess population assessment. In a few studies, generalized meta-population models incorporating major features of the life history of salmonids and representative variations on key parameters affecting survival and distribution have been used to evaluate potential population response (Kucik & Ferreri, 1998; Ruckelshaus, et al. 2004, Fagan, 2002).

Key Research Gaps:

Adapting general life cycle framework to species/ESUs

- Defining an appropriate life stage framework - consider egg to parr, overwintering, freshwater migrants, estuary/nearshore ocean rearing, specific spatial relationships

Life stage dispersal rates/distributions- relationship to spatial structure in natal tributary, estuary/nearshore marine areas

- Life stage distribution patterns - given spawning in a particular location, how are the resulting juveniles distributed relative to the spatial characteristics of the drainage?

- Relating habitat conditions, harvest, and hatchery management practices to: life stage survivals, access, migration pathways - covered in responses to other questions (those responses should recognize life cycle framework)

- Inferring historical distributions - look for and evaluate ‘reference areas’ representative of historical conditions, simple ‘what-if’ models based on temp/habitat/survival assumptions, generate testable hypotheses

- Are habitat/survival relationships, dispersal characteristics affected by relative density?

- Dispersal of returning adults - What are the relationships between juvenile rearing/dispersal patterns and spawning patterns - how does juvenile dispersal relate to spatial patterns in spawning of returning adults?

Improved Risk assessment tools/principles

- Sensitivity of simple pop models to assumptions regarding survival patterns - are there ‘thresholds’ in life stage survivals?

- Incorporating uncertainty in ‘background’ survivals into risk assessments - sensitivity analyses of model results to uncertainty structure assumptions - e.g., marine survival assumptions - effects of alternative assumption sets, cycles vs. autocorrelation vs. phased analyses

- Spatially explicit risk assessments - Apply more explicit analytical tools to explore basic questions adapt spatially explicit metapopulation models (e.g., dendritic structure), individual based modeling (multiple life history/distribution patterns - random vs. deterministic, etc)

    <u>Within populations</u> - recognize distinctive dendritic patterns in spawning/juvenile rearing - are there general principles (number, size, distribution of spawning/rearing patches) that would be informative in recovery planning?

Among populations - Are there general principles (number of pops, distribution/population size relationships) that would be informative in recovery planning?

Other topics

- Develop recommendations for performance measures consistent with general principles for assessing status/response (e.g., relating feasible measures to principles - spawner to out-migrant smolt, parr densities etc.

- Analyses contributing to the design of adaptive management/response measure priorities/strategies

Literature Cited

Cunjak, R.A. Winter habitat of selected stream fishes and potential impacts from land use activity. Can. J. Fish. Aquat. Sci. 53(Suppl. 1):267-282.

Emmett, R.L. and M.H. Schiewe (editors) 1997. Estuarine and ocean survival of northeastern Pacific Salmon. Proceedings of the Workshop March 20-22, 1996. Newport Oregon. NOAA Tech. Memo. NMFS-NWFSC-29. 313 p.

Fagan, W.F. 2002. Connectivity, fragmentation and extinction risk in dendritic metapopulations. Ecology 83(12):3243-3249.

Green, C.M.. and T.J. Beechie. 2004. Consequences of potential density dependent mechanisms on recovery of ocean type Chinook salmon (Oncorhynchus tshawytscha). Can. J. Aquat. Sci. 61:590-602.

Healy, M.C. 1991. The life history of Chinook salmon (Oncorhynchus tshawytscha). In C. Groot and L Margolis (eds.), Life history of Pacific salmon, p. 313-393. Univ. of British Columbia, Vancouver B.C.

Kocik, J.F. and C. P. Ferreri. 1998. Juvenile production variation in salmonids: population dynamics, habitat, and the role of spatial relationships. Can. J. Fish. Aquat. Sci.(Suppl. 1) 191-2000.

Kruzic, L.M., D. L. Scarnecchia and B. B. Roper. 2001. Comparison of midsummer survival and growth of age-zero hatchery coho salmon held in pools and riffles. Trans. Amer. Fish. Soc. 130:147-154.

McElhany, P., M.H. Ruckelshaus, M.J. Ford, T.C. Wainwright and E.P. Bjorkstedt. 2000. Viable salmonid populations and the recovery of evolutionarily significant units. NOAA Tech. Memo. NMFS-NWFSC-42. 154 p.

Nickelson, T.E. and P.W. Lawson. 1998. Population viability of coho salmon, Oncorhynchus kisutch, in Oregon coastal basins: application of a habitat based life cycle model. Can. J. Fish. Aquat. Sci. 55: 2383-2392.

Ruckelshaus, M., P. McElhany, M. McClure and S. Heppell. 2004. How many populations are needed for persistence of listed salmon species? Exploring the effects of spatially correlated catastrophes. In R. Ackakaya and M. Burgman (eds.) Species Conservation and Management: Case Studies. Oxford Univ. Press, *in press*.

Zabel, R.W. and S. Achord. Relating size of juveniles to survival within and among populations of Chinook salmon. Ecology. 85(3):795-206.

2. What are the cumulative, integrative effects of recovery actions on ESU viability?

Background

Simply identifying the numbers of individuals necessary for species or ESU viability is not a sufficient conservation goal alone, because the population structure of a threatened or endangered species can have a significant effect on the likelihood that the species persists (Hanski and Gilpin 1997). In spite of the clear importance of the distribution and number of populations to species persistence, it is surprising to note that a number of broad-ranging conservation recovery documents do not include explicit targets for the numbers of populations needed for species viability.

The Evolutionarily Significant Unit (ESU) is the listed entity under the Endangered Species Act, and therefore the biological characteristics of a viable ESU must be clearly stated as part of developing delisting criteria. ESU viability criteria are identified in Phase I of recovery planning, and these criteria include factors that should be evaluated when determining the characteristics and distribution of populations needed to sustain the ESU. In practice, TRTs are aiming to present biologically based criteria for evaluating whether particular combinations of population characteristics constitute a viable ESU. A viable ESU is similar to a viable population—it is naturally self-sustaining and has a negligible risk of extinction (McElhany et al. 2000). The time frame over which the risk of extinction is considered at the ESU level is a minimum of 100 years, and could be up to several hundred years. The evaluation of risk at the ESU scale involves assessing the effects of the number of populations at different risk levels, their spatial distribution, and their characteristics (i.e., diversity) in the ESU (Ruckelshaus et al. 2003).

Policy Implications

Our approach to specifying ESU viability criteria is aimed at identifying scenarios to minimize risk to the ESU, where risk is a function of the likelihood of catastrophes occurring and the consequences of losing populations with important abundance, productivity, diversity, or spatial location. Once the guidelines have been clearly established, TRTs and their regional policy groups will use them to identify scenarios of population status and characteristics that will result in a low risk ESU and maintain sufficient diversity to allow for its persistence into the foreseeable future.

Current Understanding

Conceptually, the main issues the TRT needs to address in developing criteria for determining ESU-level viability were laid out in the Viable Salmonid Populations (VSP) document (McElhany et al. 2000). In short, the ESU viability guidelines include consideration of the risk of catastrophes, maintenance of metapopulation-type processes such as dispersal among populations, and preservation of some representation of the historical diversity of the ESU. The aim of applying the ESU viability guidelines introduced in the VSP document is to determine (1) how many and (2) which **viable** populations are necessary for a naturally self-sustaining ESU. "Viable" in this sense refers to a naturally self-sustaining population that has a negligible risk of extinction over a 100-year time frame. In practical terms, a population must have certain characteristics to be considered viable—a viable population must have sufficient numbers of:

naturally produced spawners, ratio of juveniles per adult, diversity of life history and genetic types, and distribution of fish throughout the watershed (see McElhany et al. 2000). The biological analyses that we conduct are therefore aimed at addressing the following questions: (1) how many populations are necessary for ESU persistence? and (2) what suites of population characteristics will add up to a viable ESU?

There are likely to be additional populations in a recovered ESU that do not meet the strict VSP criteria for viable. For example, such populations could have many spawners that are of hatchery origin. Alternatively, a non-viable population could have sufficient numbers of naturally produced spawners but they are not well distributed throughout the watershed, or they are not representative of native diversity thought to be necessary for ESU viability. The net contributions of all populations (i.e., those that are viable and those at higher risk) to ESU status will be evaluated as part of the biological determination of whether a particular ESU scenario is viable.

Criteria for a viable ESU focus on minimizing risk and maximizing resiliency of the ESU to catastrophic events or to environmental changes that occur too rapidly for population adaptation. McElhany et al. (2000) suggest using historical patterns of population number, distribution, and diversity as a reference against which to evaluate ESU viability, since an historical ESU was very likely viable. There is considerable theoretical work on the expected viability of meta-populations (Hanski and Gilpin 1997), but because of the difficulty in meeting simplifying assumptions of metapopulation models for salmonids and their data-intensive nature (Rieman and Dunham 2000, Isaak et al. 2003), existing applications are relatively simple. Thus far, such theory has been used to roughly estimate how many salmon populations (e.g., Ruckelshaus et al. 2004), or what average population growth rates should be in order for the ESU to have a negligible risk of extinction (e.g., Holmes 2004). In addition, a few preliminary efforts have been made to relate salmon population diversity characteristics, their spatial distribution, and population risk levels to overall persistence of listed ESUs (Ruckelshaus et al. 2002, McElhany et al. 2003).

Key Research Gaps

As mentioned above, simple metapopulation models can provide estimates of the minimum number of populations needed for ESU persistence (e.g., Ruckelshaus et al. 2004, Holmes 2004). These simple metapopulation model predictions are based on estimates of population size, growth rate, dispersal among populations, and the extent to which population risks in the metapopulation are correlated. Although these metapopulation models are simple, they are very difficult to parameterize given available information, and they do not include the contribution of population diversity to ESU persistence. Additional analyses are needed to estimate the number and characteristics of populations in an ESU and how those attributes can be related to ESU persistence.

The key questions that must be addressed in order to develop ESU viability criteria are briefly noted below.

Spatial extent of correlated threats and selective environments

An important, generally unknown attribute of ESUs is what geographic sub-regions within the ESU have correlated likelihoods of catastrophic risks and similar ecological characteristics. Addressing this question provides information for determining how the distribution of naturally self-sustaining populations throughout an ESU affects its likelihood of persistence.

- What is the spatial scale over which catastrophic risks to populations are correlated?
- What are habitat and other environmental characteristics that best describe the major selective environments experienced by salmon populations?
- How are salmon diversity characteristics related to habitat and other environmental attributes?

In practice, we have performed a few simple analyses of the distribution and intensity of potential catastrophic risks (e.g., McElhany et al. 2003), which help to identify areas in which populations are expected to have similar likelihoods of falling victim to the same catastrophes.

Evaluations to date of the spatial extent of similar selective environments have involved using EPA ecoregions and major marine basins as surrogates for major distinctive environmental conditions experienced by the salmon (Ruckelshaus et al. 2002, McElhany et al. 2003, McClure et al. 2004). In addition, an analysis linking hydroregion characteristics to Chinook life history diversity in Puget Sound suggests that characteristics of the hydrograph, elevation and precipitation are predictive of some life history attributes (Beechie et al. 2004). Linking spatial and temporal differences in environmental characteristics salmon experience to the expression of life history and genetic diversity would help greatly in providing more scientific guidance on which areas historically contributed to important diversity in an ESU. In addition, answers to the question below concerning the fitness consequences of diversity are important to help in identifying those environmental/habitat features that are the best predictors of adaptive salmon diversity attributes.

Metapopulation processes and ESU persistence

- Given the distribution of population risk levels within each sub-region or across the entire ESU region, what is the corresponding likelihood of ESU persistence?
- What is the role of suitable but unoccupied habitats in ESU persistence?
- How do connectivity and other metapopulation processes contribute to ESU persistence?

Going beyond existing applications of metapopulation concepts to estimating salmonid ESU persistence will involve a combination of modeling efforts and collection of field data to help parameterize and interpret metapopulation models. Further modeling efforts could include such improvements as incorporating information on inter-population dispersal and exploring the effects of density dependence, capacity limitation, or variation in population growth rates on ESU persistence (Holmes 2004). Empirical information on occupancy of habitat patches over time, their connectivity, and how such metapopulation attributes affect overall ESU status will help in offering guidance on how to construct or evaluate ESU recovery scenarios. Examples of empirical descriptions of some of these metapopulation features exist for bull trout (Rieman and McIntire 1995, Rieman and Dunham 2000, Rich et al. 2003).

Population diversity characteristics and ESU persistence

- Of the major diversity groups that historically occurred within the ESU, how does their representation in alternative ESU scenarios relate to ESU persistence?
- How evolutionarily labile are diversity traits of salmon populations and ESUs?

Answering these two key questions linking diversity attributes of populations to ESU persistence will help to design recovery actions that will increase the likelihood that ESU diversity will contribute positively to ESU recovery. Addressing these questions will involve asking such questions as how quantitative trait and discrete genetic diversity characteristics of salmon populations are related to the persistence of the ESU, and the ways in which salmon diversity characteristics relate to individual fitness and population status (Wang et al. 2002). Understanding how rapidly salmonid life history traits can evolve in response to changes in environmental conditions (e.g., Hendry et al. 2000, Gustafson et al. 2001, Hendry et al. 2001) helps in assessing how critical a particular diversity type is to ESU persistence. Furthermore, retrospective studies (e.g., Hilborn et al. 2003) or models can be instrumental in understanding the relative contributions of diversity types to ESU persistence.

Literature Cited

Beechie, T., E. Buhle, M. Ruckelshaus, A. Fullerton and L. Holsinger. 2004. Hydrologic regime and the conservation of salmon life history diversity. In review

Hanski, I. & Gilpin, M. E. 1997 *Metapopulation biology: Ecology, Genetics and Evolution.* San Diego: Academic Press.

Hendry, A., J. K. Wenburg, P. Bentzen, E.C. Volk and T. P. Quinn. 2000. Rapid evolution of reproductive isolation in the wild: Evidence from introduced salmon. Science 290: 516-518.

Hendry, A., J. K. Wenburg, P. Bentzen, E.C. Volk and T. P. Quinn. 2001. Response to Gustafson et al. 2001. Science 291: 252.

Holmes, E. 2004. Viability analysis for endangered metapopulations: A diffusion approximation approach. *In press*.

Gustafson, R., R. Waples, S.T. Kalinowski and G. A. Winans. 2001. Evolution of sockeye salmon ecotypes. Science 291: 251-252.

Isaak, D.J., R.F. Thurow, B.E. Rieman, and J.B.Dunham. 2003. Temporal variation in synchrony among chinook salmon (*Oncorhynchus tshawytscha*) redd counts from a wilderness area in central Idaho. Canadian Journal of Fisheries and Aquatic Sciences.

60:840-848.

McClure, M. and multiple authors. 2004. Evaluating the Potential for Improvements to Habitat Condition to Improve Population Status for Eight Salmon and Steelhead ESUs in the Columbia Basin. White Paper in support of the FCRPS Hydrosystem BiOp. NOAA Fisheries, NWFSC, Seattle, WA

McElhany, P., M. Ruckelshaus, M. J. Ford, T. Wainwright and E. Bjorkstedt. 2000. Viable salmonid populations and the recovery of Evolutionarily Significant Units. NMFS-NOAA technical memorandum NMFS-NWFSC-42.

McElhany, P., T. Backman, C. Busack, S. Heppell, S. Kolmes, A. Maule, J. Myers, D. Rawding, D. Shively, A. Steel, C. Steward, and T. Whitesel. 2003. Interim report on viability criteria for Willamette and Lower Columbia Basin Pacific salmonids. Willamette/Lower Columbia Technical Recovery Team Report. NOAA Fisheries NWFSC, Seattle, WA. (http://www.nwfsc.noaa.gov/trt/viability_criteria.htm).

Rich, C.F., T. E. McMahon, B.E. Rieman and W. L. Thompson. 2003. Local-habitat, watershed, and biotic features associated with bull trout occurrence in Montana streams. Transactions of the American Fisheries Society 132: 1053-1064.

Rieman, B.E. and J. B. Dunham. 2000. Metapopulations and salmonids: A synthesis of life history patterns and empirical observations. Ecology of Freshwater Fish 9: 51-64.

Rieman, B.E. and J. D. McIntyre. 1995. Occurrence of bull trout in naturally fragmented habitat patches of varied size. Transactions of the American Fisheries Society 124: 285-296.

Ruckelshaus, M., K. Currens, W. Graeber, R. Fuerstenberg, K. Rawson, N. Sands and J. Scott. 2002. Planning Ranges and Preliminary Guidelines for the Delisting and Recovery of the Puget Sound Chinook Salmon Evolutionarily Significant Unit. Puget Sound TRT document (available at: http://www.sharedsalmonstrategy.org/resources.htm.)

Ruckelshaus, M., P. McElhany and M. J. Ford. 2003. Recovering species of conservation concern: are populations expendable? Pp. 305-329. In: P. Kareiva and S. Levin (eds.) *The Importance of Species: Perspectives on Expendability and Triage*. Princeton University Press, Princeton, NJ.

Ruckelshaus, M., P. McElhany, M. McClure and S. Heppell. 2004. How many populations are needed for persistence of listed salmon species? Exploring the effects of spatially correlated catastrophes. In R. Ackakaya and M. Burgman (eds.) *Species Conservation and Management: Case Studies*. Oxford Univ. Press, *in press*.

Wang, S., J. Hard and F. Utter. 2002. Genetic variation and fitness in salmonids. Conservation Genetics 3:321-333.

II. MECHANISMS

1. What are the direct and indirect effects of physical, biological and chemical characteristics of freshwater, estuarine and marine habitats on the VSP characteristics of a population?

Freshwater Habitats

Background

The potential for freshwater, estuarine, and marine environments to support salmon depends on a combination of physical, chemical, and biological processes. Physical processes include the size and spatial complexity of streams, the geomorphology of coastlines, and climate change. Chemical processes include the transport of nutrients to streams and the loading of chemical contaminants to surface waters, sediments, and fish tissues. Finally, biological processes include the basic ecological characteristics of different aquatic and marine communities. Human activities that degrade these different habitat attributes are at least partly responsible for declines of most threatened salmon populations (Nehlsen et al. 1991). Moreover, salmon listings are largely a result of trying to manage individual species and habitat characteristics rather than managing whole ecosystems (e.g., Doppelt et al. 1993, Frissell et al. 1997). Consequently, scientists and resource managers alike have recognized that habitat restoration plans must carefully consider the watershed or ecosystem context of habitats to be successful at restoring individual or multiple species (Nehlsen et al. 1991, Doppelt et al. 1993, FEMAT 1993, Lichatowich et al. 1995, Reeves et al. 1995). However, we currently have a limited ability to quantitatively predict (1) how land uses alter aquatic habitats and ecosystem functions, (2) how these habitat changes affect the survival, reproduction, or distribution of individual salmon, and (3) how these changes ultimately impact the viability of wild salmon populations.

Policy Implications

Recovery plans must identify specific actions required to recover species, and should at least qualitatively identify how much habitat change will be sufficient to achieve population and ESU recovery goals. Our habitat research will improve our ability to identify land uses and restoration actions that have the greatest effects on aquatic habitats, food webs, and salmon populations, and will help to identify combinations of recovery actions that are likely to achieve recovery of listed ESUs. Additionally, habitat research continues to inform NOAA Fisheries' ESA consultations, evaluations of Habitat Conservation Plans, and regulatory actions taken by NOAA or other state and federal agencies to comply with the statutory provisions of the ESA.

Current Understanding

Decades of research have shown that (1) landscape processes create a dynamic mosaic of habitat conditions in river networks, and that (2) salmonid populations are adapted to local habitat conditions within that mosaic (Beechie and Bolton 1999). Therefore, it does not make sense to manage for the same habitat conditions in all locations, or to expect conditions to remain constant in any single location. Our research should avoid attempts to identify "one-size-fits-all" habitat standards (Bisson et al. 1997), or to focus on symptoms of a disrupted ecosystem (Spence et al. 1996). Rather, our research should aim to understand how root causes of physical, chemical, or biological degradation manifest themselves in each part of the river network, and how those changes alter salmon abundance, productivity, diversity, and spatial structure.

Habitat research can be organized within a two-tiered conceptual model of watershed function (Figure 1). In this model, landscape processes and land use actions affect aquatic habitats and food webs in river networks, which in turn affect salmonid viability. Distinguishing research addressing habitat-forming (or degrading) processes from research addressing fish responses to habitat and food web changes allows us to understand processes that influence habitats independently from the species that use those habitats. We can then relate abundance, productivity, spatial structure, and diversity of any species to a single suite of habitat or ecosystem metrics. Phase II research will often span both tiers of this conceptual model.

A key aim of Phase II research is to identify ongoing and future sources of salmon habitat degradation. Coastal development and increased pollution represent major threats to the sustainability of NOAA trust resources (U.S. Congress, 2004; Beach, 2002). Agricultural, urban, and residential development have well-documented and negative impacts on physical (Booth and Jackson, 1997; Beechie et al. 2001), chemical (Ebbert and Embrey, 2002; Voss and Embrey, 2000; Hoffman et al., 2000), and biological (Morley and Karr, 2002) condition of salmon habitat. However, the relative significance of these types of habitat degradation in terms of the biology or biological requirements of salmon are often poorly understood. This uncertainty makes it difficult to prioritize restoration activities in mixed-use watersheds.

Our research must also span environments ranging from semi-arid to rain forest. In general, the same types of research must be conducted regardless of ecoregion (e.g., non-point source water pollution, sediment supply, or riparian functions), but the specific processes or mechanisms addressed may vary from one ecoregion to another (Table 1). For instance, sediment supply is dominated by landsliding in most watersheds of the coast range and Cascade Mountains (e.g., Sidle et al. 1985), so understanding land use effects on landslide rates and sediment volumes is critical to identifying restoration actions such as road decommissioning or reconstruction. By contrast, sediment supply in dry rangelands of the Columbia Plateau is more a function of surface erosion and gullying (e.g., Kaiser 1967, Peacock 1994), so assessing changes in surface erosion rates is vital to identifying where modification of agricultural practices may reduce sediment supplies.

Space and Time Scales

Landscape processes operate at a wide variety of space and time scales (**Figure 2**), and many land use actions manifest themselves in habitat changes years to decades after the initial impact. Therefore, we recognize that spatial and temporal scales of assessment vary depending on the relationships under study (Beechie et al. 2003). For example, coarse resolution remote sensing data can be used to investigate regional relationships among geologic or climatic variables and ecosystem processes or salmonid populations. Similarly, remote sensing data can be used to determine the extent of impervious surface in urbanizing watersheds as an indicator of potential non-point source pollution. By contrast, detailed field data are needed to investigate how different riparian buffer treatments affect light regimes and primary productivity in specific stream reaches, or how contaminated sediments alter the local structure of macroinvertebrate communities. As a general rule, insights gained from larger scale assessments lead to investigations of specific cause-and-effect linkages at smaller spatial scales.

With this structure Phase II habitat research can strategically address topics that are important in the near term, and initiate key in-depth studies that will provide answers to difficult questions in the long term. By maintaining process-based linkages between research elements, we can more cost-effectively integrate results into a comprehensive understanding of watershed and ecosystem function, which ultimately will allow NOAA Fisheries to better administer habitat protection under the Endangered Species Act (ESA).

Key Research Gaps

There are literally hundreds of knowledge gaps that limit our ability to predict the outcome of salmon recovery actions, and more specifically to estimate the types and amounts of restoration required to achieve salmon recovery goals. Prioritizing these gaps is a necessary first step. In broad terms, most research to date has focused on impacts of forest and rangeland management on small streams. Comparatively little attention has been given to the more complex impacts of agricultural and urban land uses. Past research has also focused on issues of habitat quantity (or capacity) rather than quality, and effectiveness of in-stream restoration actions rather than on effectiveness of restoring watershed processes (e.g., Meehan 1991, Naiman and Bilby 1998, Stouder et al. 1996). Key research gaps are listed below, grouped into four broad research themes: (1) landscape processes and land use effects on aquatic habitats, (2) biological responses to habitat effects, (3) effects of watershed and habitat restoration actions, and (4) landscape ecology.

Landscape processes and land use effects on aquatic habitats

As most research has focused on forests and small streams, there is a pressing need to shift our focus towards:

- Effects of dams, agriculture, and urbanization on river-floodplain ecosystems,
- Sources, fates, and impacts of non-point source pollution on salmon and their habitats,
- Watershed-scale cumulative effects (longitudinal connectivity and lagged habitat responses), and
- Potential impacts of climate change on stream ecosystems.

Within these broad research gaps lies a host of specific questions at multiple scales. General issues that apply across these three topics include downstream translation of effects (including the problem of routing in hierarchical networks) (Benda and Dunne 1997, Benda et al. In press), time lags between land use action and habitat response (Beechie et al. 2000, Beechie 2001), spatio-temporal accumulation of multiple land use effects (Reid 1998), and identification of appropriate reference or baseline conditions (Pess et al. 2003a). A critical scale gap exists between regional-scale studies that attempt to identify correlations between landscape attributes and habitat conditions, and local-scale studies that attempt to isolate mechanisms by which land uses alter stream habitats. Hence, research linking landscape change to habitat change at a scale relevant to recovery planning is in great need (i.e., watershed scales of 10^3-10^4 km^2).

Biological responses to habitat effects

Predicting salmon responses to changes in habitat quantity or capacity has been relatively straightforward. However, it has been much more difficult to predict sub-lethal and lethal effects of changes to habitat quality, and then extrapolate these effects to responses at the population level. Key research gaps include:

- Effects of changes in habitat quality (e.g., contaminants, food resources, temperature, structure, sediment, etc.) on individual survival, reproduction, or distribution as it relates to population growth,
- Existence of density-dependence at various life stages and its potential effect on predictions of population responses to habitat change,
- Development of multi-species response metrics,
- Development of models for mixed-use watersheds that integrate physical, chemical, and biological attributes, and
- Sensitivity of models that predict fish responses to habitat change.

Across all of these questions lies the need to predict the effects of habitat changes on multiple population attributes (i.e, all four VSP parameters, McElhany et al. 2000), and to understand the role of disturbance and recovery processes in population performance (Poff and Ward 1990, Resh et al. 1988, Reice et al. 1990). In the case of water pollution, for example, large scale and long-term ecotoxicological investigations increasingly highlight the importance of a complex array of sublethal impacts on wild salmon populations (Sandahl et al., 2004; Baldwin et al., 2003; Peterson et al., 2003; Arkoosh and Collier, 2002; Meador et al., 2002; Scholz et al., 2000). Many models of fish population responses are based on scant data, and evaluation of their accuracy, biases, and precision are critical to effective recovery planning. Research should also target a better understanding of indirect (i.e., food web) pathways by which changes in aquatic habitats alter population performance (Preston, 2002). Scale again is important, as most research is at regional or site scales, with little ability to predict population or meta-population level responses to habitat change.

Effectiveness of "habitat" restoration actions

In the past, research has focused on effectiveness of small, in-stream restoration projects (Roni et al. 2002). Relatively little attention has been paid to restoration of system-wide processes and large river-floodplain systems. Key research gaps include:

- Evaluation of various types of floodplain restoration actions,
- Evaluation of point and non-point source pollution reduction measures,
- Evaluation of restoration actions that restore watershed processes,
- Evaluation of the efficacy of habitat preservation vs. habitat restoration, and
- Effects of dam removal.

Restoration research has focused on small stream restoration due to the difficulty of evaluating fish responses in dynamic, large-river ecosystems. It has also focused on simple in-stream habitat manipulations, primarily because of difficulties in monitoring effects of non-point processes and processes with long lag-times between treatment and response. These limitations have hindered our ability to predict recovery of biota (Carins 1990, Yount and Niemi 1990, Niemi et al. 1990), especially in large river-floodplain systems (Ward et al. 2001). Also, emerging evidence indicates that non-point source pollution has the potential to undermine the effectiveness of traditional in-stream restoration projects in lowland areas (Seattle PI, 2003). Each of these challenges must be overcome in order to advance our research in these three areas.

Landscape ecology

Most landscape ecology research regarding salmon has focused on simple compositional metrics at relatively small scales. Future research should broaden the suite of environmental metrics and focus on ESU-scale predictions. Three key research gaps include:

- Relationships between landscape structure (in addition to composition) and population metrics,
- Relationships between trends in landscape structure or composition and population metrics, and
- Application of landscape ecology principles within aquatic ecosystems.

Attributes of landscape structure (e.g., landscape fragmentation, patch structure) have been largely ignored as predictors of stream habitat or salmon population attributes, and trends in landscape attributes have been overlooked as potential predictors of salmon population trends. Both areas of research may contribute to our understanding of how habitat change interacts with other factors to regulate salmon populations. At smaller scales, application of principles of landscape ecology can help elucidate in-stream processes that sustain biodiversity and salmon populations within aquatic ecosystems (Townsend 1989, Schlosser 1995, Weins 2002).

Literature Cited

Arkoosh, M.R., and Collier, T.K. 2002. Ecological risk assessment for salmon: analyzing immune function to evaluate risk. Human and Ecological Risk Assessment. 8:265-276.

Baldwin DH, Sandahl JF, Labenia JS, Scholz NL. 2003. Sublethal effects of copper on coho salmon: Impacts on nonoverlapping receptor pathways in the peripheral olfactory nervous system. *Environ Toxicol Chem* 22:2266-2274.

Beach, D. 2002. Coastal sprawl: the effects of urban design on aquatic ecosystems in the United States. Pew Oceans Commission, Arlington, Virginia.

Beechie, T.J. 2001. Empirical predictors of annual bed load travel distance, and implications for salmonid habitat restoration and protection. Earth Surface Processes and Landforms 26:1025-1034.

Beechie, T., and S. Bolton. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. Fisheries 24(4): 6-15.

Beechie, T.J, G. Pess, P Kennard, R.E. Bilby, and S Bolton. 2000. Modeling recovery rates and pathways for woody debris recruitment in northwestern Washington streams. N. Am. J. Fish. Mgmt. 20:436–452.

Beechie, T.J., B.D. Collins, and G.R. Pess. 2001. Holocene and recent geomorphic processes, land use and salmonid habitat in two north Puget Sound river basins. Pages 37-54 In J.B. Dorava, D.R. Montgomery, F. Fitzpatrick, and B. Palcsak, eds. Geomorphic processes and riverine habitat, Water Science and Application Volume 4, American Geophysical Union, Washington D.C.

Beechie, T.J., E.A. Steel, P.R. Roni, and E. Quimby, editors. 2003. Ecosystem recovery planning for listed salmon: an integrated assessment approach for salmon habitat. NOAA Technical Memorandum NMFS-NWFSC-58, National Marine Fisheries Service, Seattle, Washington

Booth, D.B., and Jackson, C.R. (1997). Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. Journal of the American Water Resources Association 33:1077-1090,

Cairns, J., Jr. 1990. Lack of theoretical basis for predicting rate and pathways of recovery. Environmental Management 14(5):517-526.

Doppelt, B., M. Scurlock, C. Frissell, and J. Karr. 1993. Entering the watershed. Island Press, Covelo, CA.

Hoffman, R.S., Capel, P.D., and Larson, S.J. 2000. Comparison of pesticides in eight US urban streams. Environmental Toxicology and Chemistry 19:2249-2258.

Ebbert, J.C., and S.S. Embrey. 2002. Pesticides in surface water of the Yakima River Basin, Washington, 1999–2000—Their occurrence and an assessment of factors affecting concentrations and loads: U.S. Geological Survey Water-Resources Investigations Report 01–4211, 49.

Frissell, C.A., W.J. Liss, R.E. Gresswell, R.K. Nawa, and L. Ebersole. 1997. A resource in crisis: changing the measure of salmon management. Pages 411-446 In D.J. Stouder, P.A. Bisson, and R.J. Naiman, eds. Pacific Salmon and their Ecosystems: Status and Future Options. Chapman and Hall. New York.

Lichatowich, J., L. Mobrand, L. Lestelle, and T. Vogel. 1995. An approach to the diagnosis and treatment of depleted Pacific salmon populations in Pacific Northwest watersheds. Fisheries 20(1):10-18.

Meador, J.P., Collier, T.K., and Stein, J.E. 2002. Use of tissue and sediment-based threshold concentrations of polychlorinated biphenyls (PCBs) to protect juvenile salmonids listed under the U.S. Endangered Species Act. Aquatic Conservation Marine and Freshwater Ecosystems, 12:493-516.

Meehan, W.R. 1991. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society, Special Publication 19, Bethesda, Maryland.

Morley, S.A., and Karr, J.R. 2002. Assessing and restoring the health of urban streams in the Puget Sound basin. Conservation Biology 16:1498-1509.

Mote, P.W., E.A. Parson, A.F. Hamlet, W.S. Keeton, D. Lettenmaier, N. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R. Slaughter, and A.K. Snover. 2003. Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest. Climatic Change 61:45-88.

Naiman, R.J., and R.E. Bilby. 1998. River ecology and management: lessons from the Pacific coastal ecoregion. Springer-Verlag, New York, New York.

Naiman, R.J., D.G. Lonzarich, T.J. Beechie, and S.C. Ralph. 1992. General principles of classification and the assessment of conservation potential in rivers. Pages 93-124 In P.J. Boon, P. Calow, and G.E. Petts, eds. River Conservation and Management. John Wiley and Sons. New York.

Nehlsen, W., J.E. Williams, and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: Stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2):4-21.

Niemi, G.J., P. DeVore, N. Detenbeck, D. Taylor, A Lima, J. Pastor, K.D. Yount, and R.J. Naiman. 1990. Overview of case studies on recovery of aquatic systems from disturbance. Environmental Management 14(5):571-587.

NRC (National Research Council). 1996. Upstream. National Academy Press, Washington, D.C.

Pess, G.R., T.J. Beechie, J.E. Williams, D.R. Whitall, J.I. Lange, and J.R. Klochak. 2003a. Watershed assessment techniques and the success of aquatic restoration activities. Pages 185-2001 In R. Wissmar and P. Bisson, eds. Strategies for restoring river ecosystems: sources of variability and uncertainty in natural and managed systems. American Fisheries Society, Bethesda, MD.

Pess, G., D.R. Montgomery, T.J. Beechie, and L. Holsinger. 2003b. Anthropogenic alterations to the biogeography of Puget Sound salmon. Pages 129-154 in D. Montgomery, S. Bolton, D. Booth, and L. Wall, editors, Restoration of Puget Sound Rivers, University of Washington Press, Seattle.

Peterson CH, Rice SD, Short JW, Esler D, Bodkin JL, Ballachey BE, Irons DB. 2003. Long term ecosystem response to the Exxon Valdez oil spill. Science 302:2082-2086.

Poff, N.L. and J.V. Ward. 1990. Physical habitat template of lotic systems: recovery in the context of historical pattern of spatiotemporal heterogeneity. Environmental Management 14(5):629-645.

Preston BL. 2002. Indirect effects in aquatic ecotoxicology: implications for ecological risk assessment. Environmental Management 29:311-323.

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. Pages 334-349 *In* J.L. Nielsen, ed. Evolution and the aquatic ecosystem: defining unique units in population conservation. American Fisheries Society Symposium 17:334-349.

Reice, S.R., R.C. Wissmar, and R.J. Naiman. 1990. Disturbance regimes, resilience, and recovery of animal communities and habitats in lotic ecosystems. Environmental Management 15(5):647-659.

Reid, L.M. 1998. Cumulative watershed effects and watershed analysis. Pages 476-501 *in* R.J. Naiman and R.E. Bilby, eds. River ecology and management: lessons from the Pacific coastal ecoregion. Springer-Verlag, New York, New York.

Resh, V.H., A.V. Brown, A.O. Covich, M.E. Gurtz, H.W. Li, G.W. Minshall, S.R. Reice, A.R. Sheldon, J.B. Wallace, and R.C. Wissmar. 1988. The role of disturbance in stream ecology. Journal of the North American Benthological Society 7:433-455.

Roni, P., T. J. Beechie, R. E. Bilby, F. E. Leonetti, M. M. Pollock, and G. R. Pess. 2002. A review of site-specific restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. North American Journal of Fisheries Management 22:1-20.

Sandahl, J.F., Baldwin, D.H., Jenkins, J.J., and Scholz, N.L. 2004. Odor-evoked field potentials as indicators of sublethal neurotoxicity in juvenile coho salmon exposed to copper, chlorpyrifos, or esfenvalerate. *Canadian Journal of Fisheries and Aquatic Sciences*, 61:404-413.

Seattle Post-Intelligencer, 2003. Our troubled sound: spawning coho are dying early in restored creeks. http://www.seattlepi.com/local/107460_coho06.shtml.

Schlosser, I.J. 1995. Stream fish ecology: a landscape perspective. Bioscience 41:704-712.

Scholz NL, Truelove NK, French BL, Berejikian BA, Quinn TP, Casillas E, Collier TK. 2000. Diazinon disrupts antipredator and homing behaviors in chinook salmon (*Oncorhynchus tshawytscha*). *Can J Fish Aquat Sci* 57:1911-1918.

Stouder, D.J., P.A. Bisson, and R.J. Naiman, eds. 1996. Pacific Salmon and their Ecosystems: Status and Future Options. Chapman and Hall, New York.

Townsend, C.R. 1989. The patch dynamics concept of stream community ecology. J. N. Am. Benth. Soc. 8:26-50.

U.S. Congress, 2004. Preliminary report of the U.S. Commission on Ocean Policy. Governor’s draft, Washington, D.C.

Voss, F.D., and Embrey, S.S. 2000. Pesticides detected in urban streams during rainstorms in King and Snohomish Counties, Washington, 1998: U.S. Geological Survey Water-Resources Investigations Report 00-4098, 22 pp.

Ward, J.V., K. Tockner, U. Uehlinger, and F. Malard. 2001. Understanding natural patterns and processes in river corridors as the basis for effective river restoration. Regulated Rivers: Research and Management 17:311-323.

Weins, J.A. 2002. Riverine landscapes: taking landscape ecology into the water. Freshwater Biology 47:501-515.

Yount, J.D. and G.J. Niemi. 1990. Recovery of lotic communities and ecosystems from disturbance - a narrative review of case studies. Environmental Management 14(5):547-570.

Table 1. Regional differences in dominant ecosystem processes or functions in the Pacific Northwest, by ecoregion (CEC 1997). This table is intended only to illustrate that different processes (described in each cell) and assessments should be emphasized in different ecoregions. Important ecosystem processes vary within ecoregions, and watershed-level assessments should target those processes that are locally important within each watershed. (Note that the Columbia River estuary is in the coastal forest ecoregion, but also affects Columbia River stocks in the Western deserts and Western forested mountains.)

Watershed process or function	**Level II ecoregion**		
	Western deserts	Western forested mountains	Coastal forests
Sediment	Gullying and surface erosion (especially in agricultural areas)	Mass wasting and gullying	Mass wasting (surface erosion in agricultural lowlands)
Flood hydrology	Snowmelt dominated flood regime	Snowmelt dominated flood regime	Rain and rain-on-snow flood regime
Low flow hydrology	Diversions and dams common	Diversions common and dams	Diversions and dams less common
Riparian functions	Grasses and shrubs, some forest in floodplains	Sparse forests, shade a dominant function	Dense forests, wood recruitment a dominant function
Habitat connectivity	Culverts, dams, and dikes common; incision and floodplain abandonment common	Culverts, dams, and dikes common	Culverts, dams, and dikes common
Estuary function	NA (Columbia estuary should be assessed in relation to freshwater habitats)	NA (Columbia estuary should be assessed in relation to freshwater habitats)	Severe impacts in agricultural and urban areas
Biological integrity	Especially important in urban and agricultural areas	Especially important in urban and agricultural areas	Especially important in urban and agricultural areas

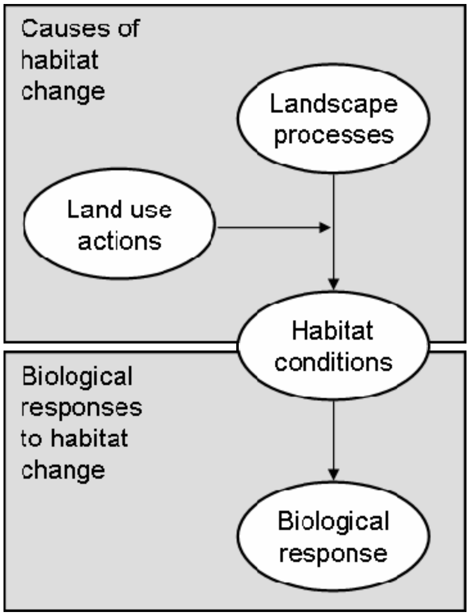


Figure 1. Schematic diagram of linkages among landscape processes, land use actions, changes in habitat conditions, and biological responses (adapted from Beechie et al. 2003).

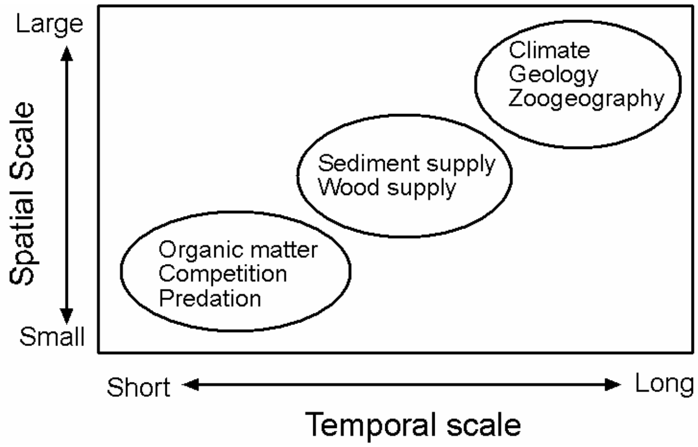


Figure 2. Spatial and temporal scales of factors that control habitat conditions and fish population responses in streams (adapted from Naiman et al. 1992).

Estuarine and Marine Habitats

Background

Linkages between habitat conditions in aquatic, estuarine and marine habitats are an important element of the life cycle based framework for evaluating salmonid recovery objectives and strategies. Research topics associated with freshwater habitats are discussed in another section of this report (Question 2). Anadromous salmonids also depend upon estuarine and marine habitats to compete their life cycle. While general patterns of estuarine and nearshore habitat use have been developed for most salmon species, key details regarding timing, distribution, relative survivals, etc. remain to be elucidated.

The availability of estuarine habitat of sufficient quality and quantity can affect all four of the basic VSP parameters for a particular salmonid population. Viable populations are characterized by a combination of average abundance (measured in terms of spawners) and productivity sufficient to cope with the relatively high year to year variations in freshwater and marine survival rates. In addition, complexity and connectivity in spatial structure provides protection against localized short-term catastrophic habitat loss. Diversity, in terms of genetic makeup and variations in life history patterns, provides a population with resilience against changes in climatic and environmental conditions on a multi-generational scale.

Policy Implications

The general approach to recovery planning for listed Pacific Salmonid ESUs recognizes populations as the fundamental units of production within an ESU. Developing and implementing successful recovery strategies will depend upon relatively accurate assessments across the landscape used by particular populations. Anadromous salmonids use estuarine and nearshore ocean habitats as juveniles and as adults. Survival of juvenile salmonids through the estuarine/nearshore ocean phase is a key determinant of year class strength. Recovery planning efforts would benefit from an improved understanding of estuarine/nearshore ocean habitat/fish interactions. Gaining a better understanding of the driving factors influencing survival reduce uncertainties regarding the level of improvements needed across the life cycle to meet recovery objectives. Increased knowledge regarding estuarine habitat/fish interactions would improve our ability to implement effective restoration actions.

Current Understanding

The development and analysis of long-term data sets on salmon production in the 1950’s and 1960’s highlighted the importance of survival through the estuarine and marine life history phases. Estuarine/marine survival is highly variable from year to year for both stream and ocean life history patterns. Cyclic or auto-correlative patterns in marine survival are common features of available data sets. Survival rates are influenced by oceanographic and climatic factors in complex ways that are not well understood. In addition, in some situations variation in climatic factors could influence survival in both marine and freshwater life stages. With some exceptions, it is difficult to identify opportunities to directly influence marine survivals. Recovery oriented population assessments have generally focused on identifying levels abundance and survival at other life stages (e.g., egg to smolt) that are sufficiently high to weather natural variations/patterns in marine survival (e.g., Nickelson & Lawson, 1998).

The patterns of habitat use within an estuarine vary among salmonid species and life history types. Juvenile pink salmon, sockeye salmon and steelhead trout typically exhibit relatively short residence times in the estuary. Chum salmon juveniles tend to spend a longer period of time in estuaries, actively feeding and growing before entry into the ocean (Healy, 1982). Chinook Coho salmon populations can include a range of life history patterns, ranging from yearling migrants that rapidly move through the estuary to the ocean to subyearlings that enter the estuary at a relatively small size, feeding and growing for a prolonged period before entering the ocean (Bottom, et al. 2001). Subyearling Chinook tend to segregate by depth during their residence in estuaries.

Populations predominated by the ocean type life history can exhibit a range of estuarine residency and ocean entry patterns. Reimers (1973) demonstrated five distinctly different patterns of seasonal movement and estuarine rearing within chinook populations inhabiting the Sixes River, Oregon. Carl & Healy (1984) reported three estuarine residency patterns for Nanaimo River chinook. In the Naniamo study, the pathway showing the highest smolt to adult survival varied among years supporting the hypothesis that life history diversity provides resilience against annual variations in climatic/oceanographic conditions.

Most estuarine studies fall into two categories: short duration assessments of localized habitats; and 2. monitoring studies emphasizing rates of migration and/or survival of larger juveniles, predominately tagged hatchery origin fish.

Key Research Gaps

<u>Landscape/Physical Processes</u>

Baseline conditions - amount and distribution of habitat
Survivals (by life stage) associated with baseline conditions
Amount of change from historical conditions

<u>Biological Effects</u>

Allocating Mortality between estuarine and ocean life history phases

Estuarine stage vs. early ocean key period: growth from smolts 100-200 mm in length to adults. High levels of natural and human induced mortalities. Key research topic: segregating survival rates associated with estuarine rearing from ocean rearing.

<u>Ocean</u>

Relationships between physical forcing and ocean growth and survival

Distribution/migration patterns, how do currents and other physical factors affect distribution and migration of juvenile and adult salmonids? Are there consistent differences in distribution and/or survival response at the population level? At the regional or ESU level?

How do variations in upwelling affect marine survival? Do wild and hatchery salmonids have different growth and survival rates in nearshore ocean

What causes regime scale changes in survival? Are population or ESU level patterns in marine survival related to particular oceanographic/climatic indices?\

Estuary

Distribution and resident times of salmonid life history stages within estuaries.

Studies should include assessments across the range of estuarine settings including large basin estuaries emptying directly into the ocean (e.g. Columbia River, Rogue River), smaller river systems emptying directly into ocean areas, river systems entering large basins (e.g., Puget Sound and Georgia Strait drainages).

Estuary use by juveniles originating upstream likely varies as a function of upstream distance to the natal production area. Very few studies have been done on pathways (timing and habitats) used by specific populations.

Salmonid responses to estuarine changes on a landscape scale.

Most knowledge about juvenile salmonid/habitat relationships within estuaries has been generated from relatively localized impact assessments and studies. Priorities in this area include assessments of relationships between the quantity and spatial distribution of estuarine habitat types and survival/dispersal of juvenile and adult salmonids.

Predation rates/relationships:

Gaining a better understanding of the Predation rates on juvenile salmonids should continue to be a high priority research topic. Priority research topics include:

Salmonid survival under differing exposure to predation;

Relationship of predation rates to estuarine habitat conditions (distribution of habitat types, quality of available habitat).

Distribution/movement of predators, vulnerability factors (size, depth distribution, etc).

Biological Response to Habitat Effects

Evaluating the effect of degraded or lost habitats on salmonid populations is particularly difficult in estuarine and nearshore ocean areas. Survival estimates for specific residence times/habitat areas are difficult to obtain. When specific survival rates are available for populations or major production areas those rates reflect cumulative survivals including freshwater rearing, estuarine residency and ocean life history stages. Research topics should include:

Spatial habitat requirements in the estuary for alternative life history patterns of ocean type and stream type salmonids. Especially in larger river systems, evaluating the relationship; between survival and the availability of a continuum or series of suitable habitat patches from natal tributaries to the estuary.

Survival responses (direct and delayed) to changes in ocean/estuary entry timing, sublethal temp/pesticides etc

Predation responses – relationship to changes in habitat conditions

Temperature/Flow alterations (impact on estuarine rearing/migration): effects on quantity of accessible habitat, growth rates, exposure to predation, etc.

Survival impacts of anthroprogenically induced changes (e.g., the size and duration of the spring plume)

Effectiveness of restoration actions

Population level responses to habitat restorations, changes in relative distribution among habitat types, survival effects, responses in terms of variation in life history patterns at the population level.

Literature Cited

Bottom, D.L., C.A. Simenstad, A.M. Babtista, D.A. Jay, J. Burke, K. K. Jones, E. Casillas and M.H. Shiewe. 2001. Salmon at River's End: the role of the estuary in the decline and recovery of Columbia River salmon. U.S. National Marine Fisheries Service. Draft manuscript. 271 p.

Carl, C.M. and M.C. Healy. (1984) Differences in enzyme frequency and body morphology among three juvenile life history types of Chinook salmon (Oncorhynchus tshawytscha) in the Nanaimo River, British Columbia. Can. J. Fish. Aquat. Sci. 41:1070-1077.

Emmett, R.L. and M.H. Schiewe (editors) 1997. Estuarine and ocean survival of northeastern Pacific Salmon. Proceedings of the Workshop March 20-22, 1996. Newport Oregon. NOAA Tech. Memo. NMFS-NWFSC-29. 313 p.

Green, C.M.. and T.J. Beechie. 2004. Consequences of potential density dependent mechanisms on recovery of ocean type Chinook salmon (Oncorhynchus tshawytscha). Can. J. Aquat. Sci. 61:590-602

Healy, M.C. 1991. The life history of Chinook salmon (Oncorhynchus tshawytscha). In C. Groot and L Margolis (eds.), Life history of Pacific salmon, p. 313-393. Univ. of British Columbia, Vancouver B.C.

McElhany, P., M.H. Ruckelshaus, M.J. Ford, T.C. Wainwright and E.P. Bjorkstedt. 2000. Viable salmonid populations and the recovery of evolutionarily significant units. NOAA Tech. Memo. NMFS-NWFSC-42. 154 p.

Nickelson, T.E. and P.W. Lawson. 1998. Population viability of coho salmon, Oncorhynchus kisutch, in Oregon coastal basins: application of a habitat based life cycle model. Can. J. Fish. Aquat. Sci. 55: 2383-2392.

Reimers, P.E. 1973. the length of residence of juvenile fall Chinook in Sixes River, Oregon. Res. Pap. Fish Comm. Oreg. 4(2): 40 p.

Rich, W.H. 1920. Early history and seaward migration of Chinook salmon in the Columbia and Sacramento Rivers. U.S. Bur. Fish. Bull. 37:2-73.

Zabel, R.W. and S. Achord. Relating size of juveniles to survival within and among populations of Chinook salmon. Ecology. 85(3):795-206.

4. What are the direct and indirect effects of alternative hydropower management activities on the VSP characteristics of a population?

Background

The construction and operation of hydropower and irrigation dams on rivers along the west coast of North America contributed to the decline of anadromous salmon populations and continues to affect them. Some dams have blocked access to historic spawning areas and others have altered the migratory corridor leading to increased direct and indirect mortality for remaining salmon populations. Dams on smaller river systems draining from mountains adjacent to the Pacific coast generally exist in headwater regions and lack provision for fish passage, thus, extirpating populations of anadromous fish that historically spawned and reared above them. Hydropower and irrigation dams in interior regions exist on both small and larger river systems. Large or high-head dams have blocked access to historic spawning and rearing areas in the upper main-stem reaches of the Columbia, Snake, Klamath, and Sacramento River basins, and on major tributaries to these rivers. These dams have particularly impacted populations of stream-type Chinook salmon. Provision for adult (and sometimes juvenile) fish passage mostly occurs at small, low-head irrigation dams on low gradient tributary rivers and at the large main-stem hydroelectric dams on the Columbia River. Downstream passage through pools and reservoirs of these dams impacts juvenile migrants, while the reservoirs have eliminated much of the historic main-stem spawning habitat for fall Chinook salmon. Dams have directly decreased natural populations of anadromous fish to much below historic levels, and without dam removal, historic populations of natural spawners cannot exist.

Nonetheless, despite the ESA listing of many salmon populations that exist in river systems heavily impacted by dams, salmon populations persist. Some of this we attribute to the many physical and operational changes implemented by dam operators in attempts to minimize impacts on anadromous salmon populations. For example, on the Columbia River where dams have fish passage facilities installed, direct measures of survival suggest that dams do not directly limit salmon populations (Kareiva et al. 2000). Thus, the majority of deleterious effects resulting from dam passage, to the degree that they exist, occur from indirect effects that express themselves outside of the direct impacts from dams and reservoirs. Determining the extent to which direct and indirect effects of hydropower dams negatively affect salmon populations, in the context of all other factors influencing salmon populations, will help define additional measures needed to lower dam impacts and assure salmon survival.

Policy Implications

Nearly all dams that have sufficient head on any river systems impacting salmon populations have multi-purpose uses, including hydropower, irrigation, flood control, and recreation. Although the Fish and Wildlife Coordination Act, 1934; Federal Power Act, 1935; Endangered Species Act, 1973; and the Pacific Northwest Electric Power Planning and Conservation Act, 1980 all have provisions to address dam impacts on anadromous fish populations (Williams and Tuttle 1992), the multi-use authorizations for the dams complicates the ability to prescribe changes at dams solely for the benefit of fish species. As the human population density on the West Coast of the United States increases, demands for uses of water will increase. The needs for water uses other than for salmon may sufficiently alter natural hydrographs under which anadromous salmonids evolved, such that permanent impacts to salmon will maximum recovery potential for many stocks. Developing policy on hydropower operations to improve salmon survival will need to take place in forums where other water users will have demands that counter potential beneficial uses for salmon. Clearly, this has already occurred in the Columbia, Sacramento, and Klamath River basins.

Current Understanding

Direct effects of dams:

Dams directly impact migrants both during passage associated with "the concrete" and as a result of changes in flow associated with the reservoirs behind them. Efforts to design, construct, evaluate, modify, and improve salmonid fish passage facilities at "the concrete" have occurred over the last 70 years, and have led to criteria for effective designs that will minimize adverse impacts to migrant fish (NMFS 2004). Adult fish can ascend well-designed ladders of nearly any length, and they do so with high success rates at most dams with installed ladders. Further, it appears feasible to install and pass adult fish over all existing dams that presently lack fish ladders. Without major changes in dam operation (most likely involving lowering of reservoirs behind dams during juvenile migration periods), it does not appear very feasible to provide effective passage conditions for juveniles. This results because juvenile fish do not have the capability to sound to the depths of deep turbine intakes. As juvenile fish tend to migrate with higher velocities and greater flow, past efforts at some dams to build effective surface passage outlets for juvenile fish have generally not succeeded because either too little flow existed in the reservoirs to move fish, or the surface outlets had too little flow to successfully attract fish compared to other outlets (mainly turbines) at the dams.

Where fish passage facilities exist, dams do not generally increase the amount of time adults spend migrating upstream, except possibly under conditions of very warm water temperatures. Although the process of finding and ascending fish ladders may cause some adult delay, fish cover the ground in reservoirs much more quickly because they swim through slow or slack water. Thus, it appears that overall timing for adults remains similar to un-dammed conditions.

Dams and reservoirs, however, have generally altered historic travel time of juvenile migrants. Reservoirs decrease the average water velocity. For example, in the Columbia River system, for smolts that migrate through the 8 or 9 main-stem dams, on average, they arrive below the hydropower system an estimated several weeks later than they would have under the same flows without dams (Williams et al. 2004).

Direct juvenile survival from dam passage

Spill: Historically, dams spilled water when flow exceeded powerhouse capacity. When spill did not cause high levels of gas supersaturation, and extreme turbulence did not exist, survival of juvenile fish passing through spillways generally neared 100%. Recently, spill for juveniles has occurred at some dams under conditions of low flow. Without attention to hydraulic patterns in the spillway basin, spill bay location within the spillway relative to the spill pattern used, deflector elevation relative to tailwater elevation and total river flow, and spill-gate opening, juvenile survival can drop to considerably less than 98%.

Juvenile Bypass systems: Screened bypass systems at major hydropower dams generally cause descaling rates ranging from approximately 2 to 5 %. For some species (sockeye salmon in particular), and depending on the level of smoltification, descaling rates may exceed this range. Direct mortality of juvenile fish passing through bypass systems generally does not exceed 2%.

Turbines: Estimates of survival through Kaplan turbines has generally ranged from the low 80% to low 90% range. Thus, passage through turbines has the largest direct impact on survival of juveniles passing dams.

Direct adult survival from dam passage

Recent evaluations of PIT-tagged adult salmon in the Columbia River indicated survival rates between Bonneville and Lower Granite Dams ranged from approximately 80 to 90% (97 to 98% per dam). Presumably, adult salmon had some mortality migrating upstream through the lower Columbia and Snake Rivers prior to dam construction, thus these present high rates of survival may match or exceed historic rates.

Indirect impacts of dams:

The largest and most controversial potential impact from dams relates to latent mortality. We define latent mortality associated with dams as any mortality that occurs after fish pass downstream of all dams as juveniles (or upstream as adults) that would not have occurred if the dams did not exist. Latent mortality might result from changes in migration timing, injuries or stress incurred during migration through juvenile bypass systems, turbines, or spill at dams that does not cause direct mortality, or disease transmission or stress resulting from the artificial concentration of fish in bypass systems or transportation barges (the latter in the Columbia River system) (Williams 2001; Budy et al. 2002). It might also occur due to depletion of energy reserves from prolonged juvenile migration (Congleton et al. 2004), altered conditions in the estuary or on entry to the ocean as a result of construction or operation of upstream storage reservoirs and dams, or disrupted homing mechanisms in adults.

Comparing smolt-to-adult return rates (SARs) with estimates of survival through the Columbia River hydropower system (for both juveniles migrating downstream and adults migrating upstream) clearly indicates that the majority of mortality suffered during the smolt-to-adult life stage occurs outside of the hydropower system (Kareiva et al. 2000).

Mechanisms related to latent mortality

Changes in water temperature that result from storing water in reservoirs may alter timing of migrations and impact growth or survival. Storage reservoirs retain heat in the fall and cold water in the spring longer than otherwise would occur. This can delay time of spawning in the fall for mainstem spawners and in the spring delay emergence from the gravel and initial growth of juveniles. This can lead toward a change in migratory timing for juveniles from what existed under natural conditions. As an example, fall chinook salmon in the Snake River now migrate through dams primarily in late June and July, whereas historically they were out of the lower river by late May to late June. Warm water released from reservoirs during the summer may also impact survival of juvenile and adult fish rearing or migrating through stretches of river considerably downstream of the reservoirs.

Decreased flows from a natural hydrograph as a result of storing water, tends to increase the migration time for juvenile smolts. This may cause fish to arrive at the estuary/early ocean later, potentially missing changes in favorable ocean conditions under which they evolved. As juveniles have limited lipid reserves, increased travel time may deplete them to levels that will decrease survival (Congleton et al. 2004). This may lead to even more deleterious impacts if an interaction exists between fish in poor condition and poor ocean conditions. No direct measurements exist to confirm this speculation.

Decreased flows in the summer coincident with warm water temperatures may also lead to lethal migratory conditions for adult salmonids, as apparently occurred in the Klamath River system for fall Chinook salmon in 2003.

Key research gaps

Understanding indirect effects of hydropower management presents the most challenge in determining how they may influence VSP characteristics of populations. Only recently with the advent of adult returns from PIT-tagged fish have we identified selective mortality related to timing of juvenile migrations, transportation, and size of fish (Zabel and Williams 2002; Williams et al. 2004). We have just recently determined that juvenile bypass systems selectively collect smaller fish as compared to those that pass through turbines and spill (Williams et al. 2004). Thus, we have no long-term information on how these selective pressures may alter salmon populations. (Williams et al. 2004) provide considerable detail on known and unknown effects of the Columbia River hydropower system on fish stocks. They conclude that future potential research should focus on 1) exploration of alternative transportation strategies, including allowing more fish to migrate volitionally, adopting seasonally varying transportation schemes, and considering ways to delay the delivery of early transported migrants to the estuary; 2) the ability of water augmentation and spill to speed up downstream migration; 3) consideration of population structure in mitigation actions to determine if actions equally benefit all segments within and between populations; and 4) how anthropogenic changes potentially create selection pressures on fish stocks, e.g., if the unprecedentedly large populations of avian predators select against larger fish.

Finally, outside of early efforts to quantify dam effects, such as blocked access to historic spawning grounds, or mortality from juveniles passing through turbines, most research that has attempted to quantify effects of dams on salmon populations has occurred over the last 3 decades. This research has provided measurements of the direct effects on salmon, and speculation about indirect effects that would account for generally decreasing salmon populations that have occurred since the early 1970s. Most of the research has occurred under ocean conditions considerable less favourable for West Coast salmon stocks. Salmon populations naturally fluctuate (see recent findings of Finney et al. (2002), which showed that Alaska sockeye salmon populations varied greatly over the past 2000 years), yet evaluations of long-term effects of dams on salmon populations (particularly in the Columbia River basin) have occurred mostly during periods when West Coast salmon populations decreased (adult returns from 1978 through 2000). Thus, some interaction between declining stocks, anthropogenic impacts on them and natural variability exists. We lack sufficient empirical evidence to support hypotheses about direct links between SARs for salmon and operation of existing dams. At present, it appears that indirect effects of dams, to the extent that they occur, will most influence population return rates. Determining the extent of the effects on top of naturally varying populations will provide a great challenge.

Literature Cited

Budy, P., G. P. Thiede, N. Bouwes, C. E. Petrosky, and H. Schaller. 2002. Evidence linking delayed mortality of snake river salmon to their earlier hydrosystem experience. North American Journal of Fisheries Management 22(1):35-51.

Congleton, J. L., and coauthors. 2004. Evaluation of physiological differences in transported, inriver migrating, and multiple-bypassed juvenile salmon. Available from Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow, ID 83844-1141.

Finney, B. P., I. Gregory-Eaves, M. S. V. Douglas, and J. P. Smol. 2002. Fisheries productivity in the northeastern Pacific Ocean over the past 2,200 years. Nature 416(6882):729-733.

Kareiva, P., M. Marvier, and M. McClure. 2000. Recovery and management options for spring/summer chinook salmon in the Columbia River Basin. Science 290(5493):977-979.

NMFS. 2004. Anadromous salmonid passage facility guidelines and criteria. National Marine Fisheries Service, Northwest Regional Office, Hydro Division. (Available at <http://www.nwr.noaa.gov/1hydrop/hydroweb/ferc.htm> - Fish Passage Criteria and Guidelines).

Williams, J. G. 2001. Potential impacts of *Renibacterium salmoninarum* on adult returns of Snake River spring-summer chinook salmon. Bulletin of the National Research Institute of Aquaculture Supplement 5:55-59.

Williams, J. G., and coauthors. 2004. Effects of the Federal Columbia River Power System on Salmon Populations. NOAA Tech Memo - In Press.

Williams, J. G., and M. E. Tuttle. 1992. The Columbia River: fish habitat restoration following hydroelectric dam construction. Pages 405-422 *in* G. W. Thayer, editor. Restoring the Nation's Marine Environment. Maryland Seagrant College, College Park.

Zabel, R. W., and J. G. Williams. 2002. Selective mortality in chinook salmon: What is the role of human disturbance? Ecological Applications 12(1):173-183.

5. What are the direct and indirect effects of alternative harvest management activities on the VSP characteristics of a population?

Background

The listing of salmon under the Endangered Species Act (ESA) has caused salmon recovery to be a main focus of salmon research at the Center. Recovery biologists are interested in the effects of harvest, hatcheries, and habitat on the four viable salmon population (VSP, McElhany et al. 2000) parameters: abundance, productivity, diversity, and spatial structure. While it is easily recognized that harvest affects abundance and spatial structure of the spawning salmon, less attention has been paid to the effect of harvest on changes in productivity and life history diversity.

As salmon abundance has declined fishery management actions have changed, directed fisheries have been greatly reduced, and new fisheries have been developed that try and protect the depressed wild populations, such as mark-selective fisheries. In the past, much of the analyses to determine sustainable fisheries levels have been based on the assumption of healthy and stable populations. Under current conditions of depressed populations levels, it is important to determine the effect of fishing pressure and the response of populations at low levels of abundance, levels low enough that depensation may be a strong factor in recruits per spawner.

Harvest is only one of many mortality factors that affect the abundance and viability of salmon stocks. Some harvest effects are immediate, while others may be manifested over decades. Many aspects of these questions can be addressed using simulation models to integrate such disparate issues as spawning habitat quality, climate variability, and harvest management scenarios (see, for example, Nickelson and Lawson 1998). An effective harvest management program must consider a wide variety of factors, habitat, hatchery, and natural, over a wide variety of time and space scales. A strong integrated modeling effort is needed to accomplish this (see question 7).

Policy Implications

Harvest regulations for Pacific northwest salmon are governed by regional councils (e.g., Pacific Fisheries Management Council), internal treaties (e.g., 1974 Boldt Decision and 1969 US v. Oregon, continuing jurisdiction of the courts), and international treaties (1991 agreement between Russia, Canada, Japan, and the U.S.) creating the North Pacific Anadromous Fish Commission to limit high seas bycatch of salmon and the 1985 Pacific Salmon Treaty with Canada regulating coastal harvest on commingling stocks, Burke 1994), as well as by the Endangered Species Act (Littell 1992). All these bodies recognize the depressed state of salmon abundance in the Pacific Northwest and utilize the best science available in making decisions about the amount of harvest to be allowed. Sometimes it appears that policy overrules science, although in most cases both factors are considered. Policy is influenced by public opinion and lobbying, such that decisions are not made solely on scientific input. Scientific output has a degree of uncertainty in the estimations made, and human nature is to disregard unfavorable output when uncertainty is expressed. Research that helps to fill our information gaps about the survival of salmon and the effects of particular harvest practices can only help to inform the process and reduce uncertainty. Model predictions can be improved and ambiguity in the scientific advice presented to policy makers and the public can be reduced.

Current Understanding

Impacts of harvest on spawning abundance has been much observed and studied; however, the impact of harvest on salmon productivity, diversity, and spatial structure is less understood. However, it has long been understood that both time/area regulations and gear types can lead to selectivity of fish being caught. Ricker (1981) noted a correlation between declining age and size of all salmon species caught in commercial fisheries since the early 1950s. Studies looking at salmon age and size since 1970 have shown decrease in size, but increase in age at maturity (Ricker 1994, Bigler et.al 1996). This corresponds with an increase in ocean productivity of salmon, due largely to increased hatchery contribution. At least two hypothesis can account for this recent declining body size: density dependent growth in the ocean and selection of larger, older fish by selective fisheries. The Bigler et al. (1996) and other recent studies support the density dependence hypothesis related to environmental factors affecting ocean productivity. Labelle et al. (1997) found correlations between various hatchery practices and coho survival, but not with harvest.

Time/area closures were developed, in part, to provide escapement over the entire time span of returning adults and to allow spawning in multiple areas. Walters and Cahoon (1985) demonstrated that to account for 90% of the production of salmon in southern British Columbia, one had only to examine half as many streams as in 1950. The authors suggested the loss in spatial diversity was due in part to increased harvest rates in the fisheries and pointed out that deliberate shaping of fisheries to recovery some of the depressed stocks was partially successful.

As wild salmon abundances declined, fishery regulations were introduced to protect certain stocks, e.g. non retention commercial fisheries, catch and release recreational fisheries. With these types of fisheries, the estimation of incidental mortalities became more relevant. Estimates of gear related incidental mortalities resulted in large variances between studies. Incidental mortality of salmon in salmon fisheries is currently accounted for in most harvest models. The Chinook Technical Committee of the Pacific Salmon Commission has developed fisheries and gear specific estimates for incidental mortalities of chinook salmon (PSC 2004).

Bycatch of salmon in nonsalmon fisheries has been addressed by the North Pacific Anadromous Fish Commission. Although salmon bycatch has been reduced, some still exists. The at-sea-Hake fishery is reported to take up to 11,000 chinook per season in the bycatch (NMFS 2003). There are no estimates of area of origin of these salmon (e.g., Alaska, Canadian, Pacific Northwest) let along estimates at the population level. Observer programs are conducted by NOAA under the groundfish program, continuing to monitor bycatch of all species with the aim of reducing bycatch.

Modeling based on quantitative genetic parameters from one population (which?) has suggested that Pacific salmon populations exposed to ????? could exhibit morphometric and life history evolution, although it has not been possible to retrospectively demonstrate harvest-mediated evolution in any salmon population (Hard 2004).

Empirical evidence for a causal link between harvesting and declines in genetic diversity in populations of fish species is limited, the evidence that does exist suggest that intense harvesting can erode genetic diversity over very short time scales (Smith et al. 1991). For salmon the period of intense harvest is past. Could the resulting reduced genetic diversity, if it did occur, have helped to cause the drastic decline we saw in the last couple of decades?

Key Research Gaps

The key research gaps for understanding the effects of harvest on the VSP characteristics of salmon populations and ESUs are:

Harvest impacts on returning abundance

- **Improving the precision and scope of estimating incidental (non-landed) fishery mortalities in salmon fisheries.** There are currently estimates of incidental mortality for most salmon fisheries, although the estimates are imprecise. They often rely on estimates of encounter rates as well as estimates of mortality from the encounter. The mortality may be immediate (such as being squished in a gillnet as it is rolled up) or delayed (such as delayed mortality in drop-off or released fish), the later being more difficult to observe and estimate. In addition, as fisheries are modified and change gear specifications, new estimates of incidental mortalities are needed, e.g., catch-and-release in both commercial and recreational fisheries (often involves multiple releases). As mark-selective fisheries are implemented to reduce fishery impacts on natural, unmarked salmon stocks, incidental mortality is increasing. Studies to determine fisheries specific incidental mortalities are generally considered costly to do (NOAA 2003).

- **Estimating stock specific bycatch[1] of salmon in non-salmon fisheries.** Bycatch of salmon has been greatly reduced in ocean non-salmon fisheries in the past decade, largely through the high-seas observatory program. However, bycatch does still occur. As stock/population estimates are not available for these bycatches, estimates are not incorporated in salmon harvest models used by the Council or Pacific Salmon Treaty processes. A theoretical simulation model exercise might give us an idea of the potential range that this source of mortality contributes to total harvest mortality. How it compares with other human induced mortalities from the other Hs will be unknown until (if) we get estimates of those mortalities. For stock/population identification of bycatch, see next item (1c).

- **Developing new approaches to estimating population specific landed catch.** For chinook salmon, the method currently used is based on cwt-recovery of indicator hatchery stock. As salmon abundance and harvest level decline, CWT sample sizes become small and estimates less precise. Innovative methods of determining population composition are needed, such as microsatellite DNA analyses. Multi-agency collaboration is required to obtain coastwide standards for genetic stock identification. The NWFSC is working on this, through collaboration with the CTC, PSC. The method, when developed, could also be used on discarded salmon in non-salmon fisheries having observer programs.

---

[1] Bycatch is defined by the Magnuson-Stevens Act (Section3(2) 1996) to be “fish which are harvested in a fishery, but which are not sold or kept for personal use, and includes economic and regulatory discards. Such term does not include fish released alive under a recreational catch and release fishery management program”.

Harvest impacts on capacity.

- Harvest is probably not a major influence in affecting capacity and immediate needs for research are not seen. Capacity, measured in numbers of fish, is generally affected by the amount of suitable habitat available at different stages in the life cycle. Capacity for one population can be reduced, however, by having to share the space with other fish such as hatchery production. If harvest removed the hatchery fish returning to natural spawning grounds, it could be increasing capacity for the wild fish.

Harvest impacts on productivity.

- **Developing harvest approaches that allow for increased productivity of populations**. A comparison of harvest management techniques, such as harvest rate versus escapement goal, fixed versus abundance controlled, and ocean versus terminal fisheries, to determine if they differentially remove more productive fish from the spawning returns?

- **Comparing fixed versus abundance based management on the resilience of populations to bounce back from low abundance levels**. Given that abundance based harvest management results in higher exploitation of salmon in abundant years than in less abundant years (e.g., PST chinook management for some fisheries), could this affect the resilience of the species to bounce back after years of low survival versus a fixed harvest rate at all abundance levels? In most such step-wise harvest regimes, the practice, while allowing larger catches in years of high abundance, also allows higher escapements, but not as high as would be obtained under a fixed harvest rate.

Harvest impacts on diversity.

- **Understanding phenotypic selectivity of fisheries**. Do current harvest approaches as applied to depressed population levels preferentially remove specific phenotypes within populations due to selectivity and does this adversely affect the population's diversity, age structure, size at maturity?

- **Identifying harvest selectivity as it affects diversity within a population**. Do current non-selective and selective harvesting practices reduce genetic or life-history diversity of Pacific salmon population? Do they change the age and/or size at maturity over time for populations? Are there practices that are more salmon-diversity friendly than others? Again, this may be different for depressed and healthy populations. It may also be different for different species and ESUs of salmon.

- **Identifying potential harvest selectivity of specific populations within ESUs**. Given that some harvest practices are known to impact different salmon populations at different rates, is this occurring currently for any salmon ESU, thereby affecting the ESU diversity?

Harvest impacts on spatial distribution.

- **Identifying harvest patterns that would affect the spatial distribution returning adult salmon**. Do current harvest management regimes cause changes in the return migration and/or spawning spatial distribution of salmon populations? Timing or spatial structure of a fishery are obvious sources for this phenomena.

Harvest management tools.

- **Improving analyses and understanding of spawner-recruit dynamics, especially at low population levels.** The development of the spawner-recruit functions and the maximum sustainable yield concept occurred at more abundance levels of salmon production. At low levels of abundance, what are the effects of small population size on salmonid stocks and how does extinction risk scale with population size? When do depensatory risk factors be come stronger that compensatory production factors? What are the depensatory mechanisms operating on salmon stocks?

- **Estimation of harvest rates and escapement goals that will allow rebuilding of depressed stocks.** This is difficult at low abundances when it is difficult to determine productivity and capacity of populations. Under salmon recovery, determination of allowable harvest must take into consideration changes in habitat and environmental conditions as well as the current condition of the populations. As harvest is only one of many human induced mortalities on salmon, the problem to determine harvest rates that will allow growth of the populations as other factory (hatchery and habitat) are adjusted to increase.

- **Comparing harvest estimates from various models** (e.g., FRAM and CTC model). Different processes use different models and estimation techniques to determine harvest impacts and they do not result in identical estimates of harvest (e.g., FRAM and CTC estimates for Puget Sound chinook). In Puget Sound, the rebuilding exploitation rates calculated for the 4-d rule for Puget Sound chinook harvest utilize CWT and CTC methods, while the monitoring of exploitation rates uses FRAM. If the monitoring estimates do not reflect the recovery rates, then overexploitation could easily occur.

- **Integrating environmental, hatchery, and habitat effects into harvest models**. To understand the risks of harvest levels on depressed stocks, it is imperative to understand the co-occurring effects from other factors and the occurrence of nonstationarity, trends, and uncertainty in these other factors.

Literature Cited

Bigler, B.S., D.W. Welch, and J.H. Helle. 1996. A review of size trends among North Pacific salmon (*Oncorhynchus*). Can. J. Fish. Aquat. Sci. 53:455-465.

Burke, W.T. 1994. The New International Law of Fisheries; UNCLOS 1982 and Beyond. Clarendon Press, Oxford. 382 pp.

Hard, J.J. 2004. Evolution of chinook salmon life history under size-selective harvest. P. 315-337 in A. Hendry and S. Stearns (eds) Evolution Illuminated: Salmon and their Relatives. Oxford University Press, NY.

Helle, J.H., Y. Ishida, D. Noakes, and V. Radchenko. 2000. Recent changes in ocean production of Pacific salmon. North Pacific Anadromous Fish Commission Bulletin No. 2. Vancouver, Canada. 359pp.

Labelle, M., C.J. Walters, andB. Riddell. 1997. Ocean survival and exploitation of coho salmon (*Oncorhynchus kisutch*) stocks from the east coast of Vancouver Island, British Columbia. Can. J. Fish. Aquat. Sci. 54:1433-1449.

Littell, R. 1992. Endangered and other protected species: federal law and regulation. The Bureau of National Affairs, Inc. Washington, D.C. 185 pp plus appendices.

MSFCMA. 1996. Magnuson-Stevens Fishery Conservation and Management Act. Public Law 94-265 as amended through October 11, 1996.

National Marine Fisheries Service (NMFS). 2003. Northwest Region current bycatch priorities and implementation plan. National Marine Fisheries Service, Northwest Region, Seattle WA November 2003.

Norris, J.G. 2000. Defining equivalent exploitation rate reduction policies for endangered salmon stocks. P. 435-450 in E. Knudsen et al. (eds) Sustainable Fisheries Management Pacific Salmon. Lewis Publishers, New York.

Pacific Salmon Commission (PSC). 2002. Investigations of methods to estimate mortalities of unmarked salmon in mark-selective fisheries through the use of double index tag groups. By Selective Fisheries Evaluation Committee, Pacific Salmon Commission. SFEC (02)-1. 101pp.

Pacific Salmon Commission (PSC). 2004. Estimation and application of incidental fishing mortality in chinook salmon management under the 1999 agreement to the Pacific Salmon Treaty. By the Chinook Technical Committee, Pacific Salmon Commission. TCCHINOOK (04)-1. 56pp.

Peterman, R.M., B.J. Pyper, M.F. Lapointe, M.D. Adkison, and C.J. Walters. 1999. Spatial and temporal patterns of covariation in components of recruitment of British Columbia and Alaska sockeye salmon. P. 33-36 in Proceedings of the Symposium on Ecosystem Approaches for Fisheries Management. University of Alaska Sea Grant College Program AK-SG-99-01.

Ricker, W.E. 1981. Change in the average size and average age of Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 38:1636-1656.

Ricker, W.E. 1994. Trends in the average size of pacific salmon in Canadian catches. In Climate change and northern fish populations. Ed by R.J. Beamish. Can. Spec. Publ. Fish Aquat. Sci. No. 121. pp 593-602.

Smith, P.J., R.I.C. Francis, and M. McVeagh. 1991. Loss of genetic diversity due to fishing pressure. Fisheries Research 10: 309-316.

Walters, C.J. and P. Cahoon. 1985. Evidence of decreasing spatial diversity in British Columbia Salmon Stocks. Can. J. Fish. Aquat. Sci. 42:1033-1037.

6. What are the direct and indirect effects of alternative hatchery management activities on the VSP characteristics of a population?

Background

Hatchery production is widespread across the range of listed salmonids (Hilborn 1992, Lichatowich 1999). This production has the multiple (and sometimes simultaneous) goals of increasing harvest, fending off imminent extinction and restoring wild populations. However, neither the effects of hatchery production on wild populations, nor the efficacy of hatchery efforts in a conservation arena have been well-characterized.

Both theoretical and empirical evidence suggests that wild salmonid populations are potentially affected by hatchery fish ecologically, behaviorally and genetically (Youngson and Verspoor 1998). For instance, hatchery fish may prey on wild fish. They may compete with wild fish as juveniles in freshwater habitat, in the ocean, or as adults for spawning habitat (Fleming and Gross 1994, Einum and Fleming 1997, Berejikian et al. 1999, Fleming et al. 2000, Volpe et al. 2001). In addition, an increase in abundance due to hatchery production may affect predation rates of other predators on wild salmonids (Fresh and Schroder 2003, Nickelson 2003). Most directly, mixed-stock fisheries that include wild fish can result in a higher harvest rate on those wild fish than would otherwise be realized (Hilborn and Eggers 2000). Finally, hatchery programs can change the incidence of disease in wild populations. These effects may be realized both within species and across species (i.e. hatchery releases of one species can have effects on other salmonid species) (Levin and Williams 2002).

Hatchery programs also have the potential to affect the fitness of wild fish or the productivity of natural populations, when hatchery-origin spawners spawn in the wild (Reisenbichler and Rubin 1999, Chilcote 2003, Nickelson 2003). Hatchery programs exert domestication selection on fish included in those programs; the degree of selection pressure varies with husbandry practices. As a result of this selection, genetically-based changes in behavior and morphology have been documented in hatchery fish in as little as a single generation (Fleming et al. 2000, Fleming et al. 2002, Ford 2002, Heath et al. 2003, McLean et al. 2003, Dannewitz et al. 2004). In addition, many hatchery programs utilize fish of exogenous origin. These fish may not be adapted to local conditions. Introgression of genes from hatchery fish into wild populations thus has the potential to affect the survival and fitness of their progeny in the wild, as well as the overall productivity of the population. While the potential mechanisms for these interactions have been reasonably well-characterized, the magnitude, scale, distribution and variation of such potential impacts have not.

Hatcheries are also an important component of much conservation planning, which often includes roles for hatchery production in reintroductions, and as a short-term safety-net (NMFS 2000). They are also regularly included in an effort to restore wild populations. Intuitively, captive broodstock and safety-net programs have the potential to dramatically reduce extinction risks in the short-term. Well-planned and executed reintroduction efforts (using fish derived from captive propagation efforts) may also be an important component of conservation programs. However, because of the potential for inadvertent negative effect of hatchery programs, additional work is needed to develop best practices for implementing and removing supplementation and reintroduction programs.

Policy Implications

Currently, hatchery programs are used to fulfill tribal and treaty obligations, to provide enhanced harvest opportunities for all fishers, and as part of recovery efforts. Increasing our understanding of the impacts of different hatchery programs will help to identify combinations of actions likely to achieve recovery. Equally importantly, it will provide information to modify existing programs (if necessary) to minimize impacts on listed ESUs while still providing their other important functions. Finally, the efficiency to be gained by a greater understanding of effective supplementation and reintroduction programs will reduce expenditures of both time and money to achieve recovery.

Key Research Gaps

Recently, a cross-divisional team at the NWFSC has developed a Salmon Hatchery Strategic Research Plan. Recovery planning research aimed at the effects of hatchery management will be tightly coordinated with (and often conducted by) this group. Key research gaps for recovery planning include the following two areas:

Effects of hatchery management on the productivity, abundance, spatial structure and diversity of wild populations.

Research aimed at the effects of hatchery programs will seek to identify the magnitude of impacts (positive or negative) of hatchery programs on the abundance, productivity, spatial structure, genetic diversity and phenotypic diversity (the VSP parameters) of wild salmon and steelhead populations. There are a variety of factors that may affect the response of populations to hatchery influences. The recovery planning team is most interested in the following questions

- *What impacts on population and ESU-level characteristics (VSP parameters) of do hatchery effects have at different scales?* This question is aimed at characterizing impacts at a local scale (e.g. those due to interbreeding with hatchery spawners within a population) vs. those occurring at a larger scale (e.g. density-dependent mortality in estuarine environments).
- *What impacts do different magnitudes of release or interaction on population and ESU level characteristics (VSP parameters)?* Research in this area seeks to identify potential relationships between the number of hatchery-origin fish released, the proportion of the population composed of hatchery-origin fish and other similar variables and population status.
- *What is the effect of differing hatchery practices, or changes in hatchery practices through time on population and ESU-level characteristics (VSP parameters)?* Because hatcheries are so variable in their husbandry practices, there is enormous potential for them to have different effects on wild population VSP characteristics. Research in this area seeks to identify the magnitude and direction of those effects, associated with different husbandry practices.

All of these questions can be viewed at least in part as effectiveness monitoring for hatchery programs – they all seek to determine the outcome of these programs. In addition, each of these questions will seek to identify conspecific and interspecific effects.

We envision a similar multi-stage approach to each of these questions. The first is a large-scale retrospective analysis of population status and hatchery practices. This is an effort to use existing data to generate hypotheses about the type, direction and magnitude of potential effects. These results can be used to design appropriate experiments (steps two and three). The second step is an experimental approach that includes taking advantage of "natural" experiments, such as dramatic widespread changes in hatchery programs and expanding ongoing studies to include both greater replication and controls. We also intend to implement one or more large-scale hatchery manipulations, if logistic considerations can be adequately addressed. These experiments will examine differential survival, phenotypic characteristics, genotypic characteristics and distribution of populations across a range of factors (above). Finally, we intend to initiate additional studies of hatchery fish fitness in comparison to wild fish fitness. Importantly, in addition to providing information about potential impacts of hatchery programs, this work can also provide important information for status assessments; currently, hatchery-origin natural spawners add a high degree of uncertainty to population productivity evaluations because their reproductive success is unknown.

Effective use of hatchery programs in recovery efforts.

Because of the potential for hatchery programs to contribute to recovery efforts, the recovery planning team is also interested in the following three critical gaps:

- *Providing guidelines for reintroductions of populations or life history types.* Research aimed at this area will address questions about appropriate hatchery stock to use when the native populations have been extirpated (e.g. should anadromous fish from another population be introduced to a population with newly restored access to the ocean that has a resident component extant? or, should a re-introduction draw from the closest population, or populations with the most similar environmental characteristics?)
- *Identifying conditions under which the use of a safety net is appropriate.* Research in this area will seek to identify risk levels indicating the use of safety-net hatcheries as well as to define the terms of use for those hatcheries. For example, what is the maximum number of generations that should be maintained in a hatchery? What practices should be used?
- *Identifying conditions under which hatcheries can contribute to the restoration of a population.* In general, merely increasing a population's abundance without addressing underlying causes of decline cannot contribute to recovery. However, there may be situations in which hatchery production can have a positive benefit. Research in this arena will be aimed at characterizing the conditions under which an increase in abundance IS useful to the population's persistence and the characteristics of the fish that contribute to that increase in abundance.

Again, each of these questions contributes substantially to effectiveness monitoring for hatchery effort designed to improve population status. We will approach these questions using both theoretical (modeling) techniques to evaluate the sensitivity of population response to alternative supplementation programs and experimental work testing those hypotheses.

Coordination with and links to other components of the Recovery Planning Research Plan

This work is closely linked to two other components of the Recovery Planning Research Plan:

1. Life-cycle modeling (Question 7).

Information derived from these efforts can feed directly into work aimed at determining population responses to likely management actions (life-cycle modeling). In particular, research that identifies the magnitude and type of impacts that various hatchery practices exert on wild populations will be critical for such efforts. Importantly, however, there is a need to consider density-dependence when incorporating such results, as several studies have indicated that there are density-dependent effects (at least on growth) of hatchery fish on wild-populations (e.g. Fleming and Gross 1994, Bohlin et al. 2002). In addition, because there is likely to be some uncertainty in the likely response of wild populations to hatchery impacts, model sensitivity to these impacts should be thoroughly evaluated.

2. Exotic species (Question ?)

Many of the potential impacts of hatchery-origin fish are similar to hypothesized impacts of introduced species. Thus, as researchers work to quantify the impacts of those non-indigenous species, they will coordinate with workers addressing questions aimed characterizing at the impacts of hatchery programs.

Literature Cited

Berejikian, B. A., E. P. Tezak, S. L. Schroder, T. A. Flagg, and C. M. Knudsen. 1999. Competitive differences between newly emerged offspring of captive-reared and wild coho salmon. Transactions of the American Fisheries Society **128**:832-839.

Bohlin, T., L. F. Sundstrom, J. I. Johnsson, J. Hojesjo, and J. Pettersson. 2002. Density-dependent growth in brown trout: effects of introducing wild and hatchery fish. Journal of Animal Ecology **71**:683-692.

Chilcote, M. W. 2003. Relationship between natural productivity and the frequency of wild fish in mixed spawning populations of wild and hatchery steelhead (Oncorhynchus mykiss). Canadian Journal of Fisheries and Aquatic Sciences **60**:1057-1067.

Dannewitz, J., E. Petersson, J. Dahl, T. Prestegaard, A. C. Lof, and T. Jarvi. 2004. Reproductive success of hatchery-produced and wild-born brown trout in an experimental stream. Journal of Applied Ecology **41**:355-364.

Einum, S., and I. A. Fleming. 1997. Genetic divergence and interactions in the wild among native, farmed and hybrid Atlantic salmon. Journal of Fish Biology **50**:634-651.

Fleming, I. A., T. Agustsson, B. Finstad, J. I. Johnsson, and B. T. Bjornsson. 2002. Effects of domestication on growth physiology and endocrinology of Atlantic salmon (Salmo salar). Canadian Journal of Fisheries and Aquatic Sciences **59**:1323-1330.

Fleming, I. A., and M. R. Gross. 1994. Breeding Competition in a Pacific Salmon (Coho, Oncorhynchus-Kisutch) - Measures of Natural and Sexual Selection. Evolution **48**:637-657.

Fleming, I. A., K. Hindar, I. B. Mjolnerod, B. Jonsson, T. Balstad, and A. Lamberg. 2000. Lifetime success and interactions of farm salmon invading a native population. Proceedings of the Royal Society of London Series B-Biological Sciences **267**:1517-1523.

Ford, M. J. 2002. Selection in captivity during supportive breeding may reduce fitness in the wild. Conservation Biology **16**:815-825.

Fresh, K. L., and S. L. Schroder. 2003. Predation by northern pikeminnow on hatchery and wild coho salmon smolts in the Chehalis River, Washington. North American Journal of Fisheries Management **23**:1257-1264.

Heath, D. D., J. W. Heath, C. A. Bryden, R. M. Johnson, and C. W. Fox. 2003. Rapid evolution of egg size in captive salmon. Science **299**:1738-1740.

Hilborn, R. 1992. Hatcheries and the Future of Salmon in the Northwest. Fisheries **17**:5-8.

Hilborn, R., and D. Eggers. 2000. A review of the hatchery programs for pink salmon in Prince William Sound and Kodiak Island, Alaska. Transactions of the American Fisheries Society **129**:333-350.

Levin, P. S., and J. G. Williams. 2002. Interspecific effects of artifically propagated fish: an additional conservation risk for salmon. Conservation Biology **16**:1581-1587.

Lichatowich, J. 1999. Salmon without rivers. Island Press, Washington, D.C.

McLean, J. E., P. Bentzen, and T. P. Quinn. 2003. Differential reproductive success of sympatric, naturally spawning hatchery and wild steelhead trout (Oncorhynchus mykiss) through the adult stage. Canadian Journal of Fisheries and Aquatic Sciences **60**:433-440.

Nickelson, T. 2003. The influence of hatchery coho salmon (Oncorhynchus kisutch) on the productivity of wild coho salmon populations in Oregon coastal basins. Canadian Journal of Fisheries and Aquatic Sciences **60**:1050-1056.

NMFS. 2000. Operation of the federal Columbia River power system including the juvenile fish transportation program and the Bureau of Reclamation's 31 projects, including the entire Columbia Basin Project. U.S. Department of Commerce, NOAA, National Marine Fisheries Service, Northwest Region, NW Region, Seattle, Washington.

Reisenbichler, R. R., and S. P. Rubin. 1999. Genetic changes from artificial propagation of Pacific salmon affect the productivity and viability of supplemented populations. Ices Journal of Marine Science **56**:459-466.

Volpe, J. P., B. R. Anholt, and B. W. Glickman. 2001. Competition among juvenile Atlantic salmon (Salmo salar) and steelhead (Oncorhynchus mykiss): relevance to invasion potential in British Columbia. Canadian Journal of Fisheries and Aquatic Sciences **58**:197-207.

Youngson, A. F., and E. Verspoor. 1998. Interactions between wild and introduced Atlantic salmon (Salmo salar). Canadian Journal of Fisheries and Aquatic Sciences **55**:153-160.

7. What are the effects of ecological interactions (competition, predation, disease, etc.) and/or ecosystem characteristics on the VSP characteristics of a population?

Background

Pacific salmon and steelhead interact with hundreds of taxa during their lifespan (Cederholm et al. 2000), and the extent of ecological interactions throughout the life cycle has consequences for the viability of wild salmonid populations. The effects of ecological interactions such as predation, competition, and diseases/parasites are influenced by habitat (Poe et al. 1994), environmental stressors (Jacobson et al. 2003), presence of non-native species (Achord et al. 2003), cycling of marine-derived nutrients (Cederholm et al. 1999), and climate variability (Hare et al. 1999, Mantua et al. 1999). Research has identified a suite of ecological interactions that occur during the lifespan of Pacific salmon and steelhead. However, we are limited in our ability to predict 1) how the suite of predators, competitors, parasites-pathogens, and ecosystem characteristics influence the abundance, productivity, spatial structure and diversity of Pacific salmonid populations, and 2) what scenarios and management actions might mitigate the influence of these various ecological interactions. Incorporating the effects of ecological interactions into an overall life-cycle framework will lead to such predictability.

Policy Implications

Recovery plans must identify specific actions required to recover species, and the extent to which ecological interactions may influence the extent of or rate of recovery should be determined to achieve viable population and ESU recovery goals (McElhany et al. 2000). Our research on ecological interactions will improve our ability to identify management actions regarding interactions that have the greatest influence on salmon populations and will help identify combinations of recovery actions that are likely to achieve recovery of listed ESUs. Additionally, research on ecological interactions continues to inform regulatory actions taken by NOAA or other state and federal agencies to maintain compliance with the provisions of the ESA.

Current Understanding

Decades of research on salmon and steelhead predators have demonstrated that predators can exert significant mortality on salmonids, particularly where habitats have been permanently altered by hydropower operations (NMFS 2000). Dams and reservoirs are generally believed to increase the incidence of predation over historic levels (Poe et al. 1994) by increasing lentic habitats, disrupting habitat or prey behavior, increasing local water temperatures which increases predator digestion and consumption rates, decreasing turbidity which may increase predator capture efficiency, favoring introduced competitors which could cause some predators to shift to a diet composed largely of juvenile salmonids, and increasing stress and sub-clinical disease of juvenile salmonids, which could increase susceptibility to predation (reviewed in NMFS 2000). In addition, dam-related passage problems and reduced river discharge can affect the availability, distribution, timing, and aggregation of migrating salmonids, thereby increasing exposure time to predation, increasing exposure time later in the season when predator consumption rates are high (Beamesderfer et al. 1990, Rieman et al. 1991). Predators such as killer whales (Ford et al. 1994, 1998), striped bass (Johnson et al. 1992), crappie spp. (Karchesky and Bennett 1998), and brook trout, (Kreuger and May 1991, Maret et al. 1997) in freshwater, estuarine, and nearshore marine communities have been documented and contribute an unquantified amount of mortality of salmon and steelhead. The attraction of avian, fish and mammalian predators by releases of large numbers of hatchery fish has recently been implicated (Nickelson 2003) as impacting wild populations.

Competitors also influence survival and reproduction of Pacific salmonids via density-dependent mortality (Achord et al. 2003). In the Columbia River basin alone, over 20 species of fishes have been introduced since the late 1800s, and many of them are now well established (Poe et al. 1994). Introduced fish species exert competitive pressure on Pacific salmonids via spawning time overlap (American shad, Atlantic salmon) and/or juvenile dietary and spatial overlap with salmonid smolts during the freshwater-ocean transition (American shad, Atlantic salmon). Competition with brook trout is also likely widespread (Hutchison and Iwata 1997), possibly leading to lower salmon survival in watersheds with brook trout than those without brook trout (Levin et al. 2002). While competitive impacts may vary in relation to specific hatchery operations and habitat characteristics (Flagg et al. 2000), it is recognized that hatchery programs for Pacific salmonids may pose risks to wild salmonid populations. However, the effects of hatchery releases on wild juvenile salmonids in streams are poorly understood (Pearsons and Hopley 1999; Waples and Drake 2004).

Disease interactions, which may occur at multiple life-cycle stages for Pacific salmonids, are understudied and often indiscernible in the wild, and epidemics are often not anticipated. Pathogens reside in wild populations, and diseases can be transferred between wild and hatchery fish; however, the initial introduction of pathogens into a population may result from infected hatchery fish being transported into susceptible populations (Reno 1998). The incidence and effects of diseases on hatchery salmon and steelhead can be extensive, depending on environmental conditions, and vary considerably among the various viral, bacterial, and parasitic diseases (Waknitz et al. 2002). Despite improvements in hatchery management, diseases are a chronic problem for salmonid artificial propagation. The high densities at which hatchery populations are reared and released may increase pathogen incidence, lower transmission barriers, and lead to high virulence; this increases the risk of future epidemics within hatchery populations and hence to wild populations. Moreover dense hatchery populations may act as reservoirs for exotic pathogens, and, if hatchery fish are asymptomatic, result in accelerated transmission to wild populations (Coutant 1998). Susceptibility differences identified in wild stocks and among hatchery strains may influence proliferation of new or old virulent strains through close contact. Disease may also indirectly affect salmonid survival through compromising predator avoidance (Mesa 1998).

Ecosystem Characteristics

Intensive exploitation of Pacific salmon has led to dramatic changes in the structure and productivity of marine and freshwater ecosystems. Understanding the implications of human exploitation for ecosystem function is increasingly recognized and requires monitoring and research based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem composition, structure and function (Christensen et al. 1996). It is becoming increasingly clear that marine-derived nitrogen and phosphorous once delivered to the rivers of the Columbia River basin by spawning salmonids are a critical part of ecosystems of the Pacific Northwest. Because many of the systems in which salmon spawn and rear are inherently nutrient poor, the delivery of marine-derived nutrients by returning salmon carcasses may be crucial to survival of juvenile salmon and recovery of depleted salmon. As population growth rate of salmon is particularly sensitive to changes in egg-to-smolt survival (Kareiva et al. 2000), nutrient enhancement (e.g., carcass additions) may be used to increase population growth enough to reduce the risk of extinction. However, these techniques are highly contentious and require a mix of experimental and modeling techniques.

Fisheries (*e.g.* squid, anchovy, herring, pollock) that target salmonid prey and non-indigenous taxa that may alter habitat conditions are additional examples of ecosystem characteristics that may influence salmonid viability. The former represents direct and indirect competition with humans; during their ocean phase, salmonids forage opportunistically on a diverse assemblage of pelagic organisms, and humans directly harvest many of these organisms. The large-scale removal of salmon prey by fishing clearly has the potential to impact salmon populations as does the exploitation of species not consumed by salmon if that influences food web structure. The effects of fishing clearly include ecosystem effects, but the degree to which such effects impact salmon and interact with climatic variability is not well understood and requires sophisticated models. The latter represents effects from non-indigenous habitat-forming plant species (*e.g.* Atlantic smooth cordgrass) that require controlled manipulations or specific modifications to determine if they substantially alter estuarine and nearshore ecosystem functioning and processes. These mechanisms may indirectly influence salmonid population viability via altering competition and predation patterns, food web structure, modifying the environment or habitat, or by modifying critical ecosystem processes (such as nutrient retention, erosion, etc.).

Space and Time Scales

The effects of ecological interactions and ecosystem characteristics operate over varying spatial and temporal scales, and most land uses manifest themselves in habitat changes years to decades after the initial impact. Therefore, spatial and temporal scales of assessment vary depending on the relationships under study. For example, coarse resolution remote sensing data can be used to investigate regional relationships among geologic or climatic variables and ecosystem processes or salmon populations. By contrast, detailed field data are needed to investigate how different riparian buffer treatments affect light regimes and primary productivity in specific stream reaches. As a general rule, insights gained from larger scale assessments lead to investigation of specific cause and effect linkages at smaller spatial scales.

With this research structure, Phase II habitat research can strategically address research topics that are important in the near term, and initiate key in-depth studies that will provide answers to difficult questions in the long term. By maintaining process-based linkages between research elements, we can more cost-effectively integrate results into a comprehensive understanding of watershed and ecosystem function, which ultimately will allow NOAA Fisheries to better administer habitat protection under the Endangered Species Act (ESA).

Key Research Gaps

Multiple factors and cumulative risks

Most research has focused on single factors. Need to focus on synergistic effects:

1. Interaction of ecological factors with environment
    - Ecological interactions in pools/reservoirs
    - Ecological interactions and ocean conditions (nearshore and estuary)
    - Habitat use by wild salmonids in presence/absence of hatchery fish
2. Interactions among ecological factors
    - Disease and predation susceptibility
    - Predator enhancement (via hatchery fish, non-indigenous species)
    - Food web effects (interaction strength, bottom-up vs. top-down control)
3. Compensatory vs. additive sources of mortality
4. Predator-prey relationships (functional and/or numerical responses)
5. The importance of density-dependence and implications of assumptions

Mechanisms for ecological interactions

Most research has focused on patterns. Need critical mechanistic information on interactions, particularly with respect to hatchery and non-indigenous fish.

1. Direct effects (displacement, agonistic interactions, competition for food/space)
2. Indirect effects

Diseases in released hatchery fish and interactions with wild fish

Most research has focused on diseases in hatcheries. Need to focus on disease transmission between hatchery-origin and natural-origin fish (NRC 1996).

1. Effects of disease on released hatchery fish and interaction with wild fish

Survival/mortality data for use in overall salmonid life cycle models

Most research has focused on survival/mortality data from specific predators, diseases, times, and places. Need to explicitly quantify mortality sources for ESUs.

1. Stage-specific survival for use in demographic models
2. Sensitivity analyses of parameters

A combination of approaches (experimental, observational, retrospective analyses, modeling) will be required to address the role of ecological interactions in the recovery of Pacific salmonids, as will establish baseline conditions and monitoring the status and the effectiveness of actions. Scenario planning could be employed to examine the potential impacts of species introductions or extinctions on ecological interactions with salmon populations (see Question #8). It will be critical to identify which geographic areas/ESUs/populations are at risk from which factors, *e.g.* quantifying the number of non-indigenous species that are likely to be encountered by individuals from different populations/ESUs and the likely mechanisms of that effect (e.g. competition, predation). Current and historical or reference conditions with respect to ecological interactions need to be estimated in order to establish context for understanding the role of ecological interactions.

Determining the impact of ecological interactions on stage-specific survival requires large-scale experiments on identified competitors, predators, parasites/pathogens and ecosystem characteristics and a framework for assessing the particular ecological impact of hatchery-origin salmonids and non-indigenous species (Parker et al. 1999). In particular, large-scale experiments to quantify the various effects of hatchery-origin fish on wild salmonids are critical (see Question #4). NMFS has identified key research gaps and ongoing research concerning the effect of non-indigenous species on biodiversity changes, impacts on salmon and their associated habitats and ecosystems, the mechanisms involved, and the susceptibility of salmonid life stages are salmonids most susceptible to impacts by non-indigenous species (Feist et al. in prep.). Monitoring experiments on various mechanisms thought to be important in an ecological context is also critical to determining the effectiveness of recovery projects (see Question #9). Finally, there is a critical need, in addition to assessing the effects of ecological interactions on population abundance and productivity, to incorporate their effects on the diversity and spatial structure of salmonid populations.

Literature Cited

Achord, S., P. S. Levin, and R. W. Zabel. 2003. Density-dependent mortality in Pacific salmon: the ghost of impacts past? Ecology Letters 6:335–342.

Beamesderfer, R. C., B. E. Rieman, L. J. Bledsoe, and S. Vigg. 1990. Management implications of a model of predation by a resident fish on juvenile salmonids migrating through a Columbia River reservoir. North American Journal of Fisheries Management 10:290-304.

Cederholm CJ, Kunze MD, Murota T, and Sibatani A. 1999. Pacific salmon carcasses: essential contributions of nutrients. and energy for aquatic and terrestrial ecosystems. Fisheries 24: 6–15.

Cederholm, C. J., D. H. Johnson, R. E. Bilby, L. G. Dominguez, A. M. Garrett, W. H. Graeber, E. L. Greda, M. D. Kunze, B. G. Marcot, J. F. Palmisano, R. W. Plotnikoff, W. G. Pearcy, C. A. Simenstad, and P. C. Trotter. 2000. Pacific salmon and wildlife - ecological contexts, relationships, and implications for management. Special Edition Technical Report, prepared for D.H. Johnson and T.A. O'Neil (Manag. Dirs.), Wildlife-Habitat Relationships in Oregon and Washington. Washington Department of Fish and Wildlife, Olympia, Washington. 141 pp.

Christensen, N. L., A. M. Bartuska, J. H. Brown, S. D. Carpenter, C. Antonio, R. Francis, J. F. Franklin, J. A. MacMahon, R. F. Noss, D. J. Parsons, C. H. Peterson, M. G. Turner, and R. G. Woodmansee. 1996. The Report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management. *Ecological Applications* 6(3): 665–691.

Coutant, C. C. 1998. What is “normative” for fish pathogens? A perspective on the controversy over interactions between wild and cultured fish. Journal of Aquatic Animal Health 10: 101–106.

Feist, B. E., A. H. Fullerton, P. Roni, B. L. Sanderson, and E. A. Steel. (in prep.). Northwest Fisheries Science Center Non-Indigenous Species Research Plan. 5 May, 2004 draft.

Flagg, T. A., B. A. Berejikian, J. E. Colt, W. W. Dickhoff, L. W. Harrell, D. J. Maynard, C. E. Nash, M. S. Strom, R. N. Iwamoto, and C. V. W. Mahnken. 2000. Ecological and behavioral impacts of artificial production strategies on the abundance of wild salmon populations. U. S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-41, 92 p.

Ford, J. K., G. M. Ellis, and K. C. Balcomb. 1994. Killer Whales. University of Washington Press, Seattle, WA, and University of British Columbia Press, University of British Columbia, Vancouver, British Columbia.

Ford, J. K., G. M. Ellis, L. G. Barrett-Lennard, A. Morton, R. Palm, and K. C. Balcomb III. 1998. Dietary Specialization in Two Sympatric Populations of Killer Whales (*Orcinus orca*) in Coastal British Columbia and Adjacent Waters. Canadian Journal of Zoology 76:1456-1471.

Hare, S. R., N. J. Mantua, and R. C. Francis. 1999. Fisheries Habitat--Inverse Production Regimes: Alaska and West Coast Pacific Salmon. Fisheries 24:1069-1080.

Hutchinson, M. J. and M. Iwata. 1997. A comparative analysis of aggression in migratory and non-migratory salmonids. Environmental Biology of Fishes 50: 209-215.

Jacobson, K. C., M. R. Arkoosh, A. N. Kagley, E. R. Clemons, T. K. Collier, and E. Casillas. 2003. Cumulative effects of natural and anthropogenic stress on immune function and disease resistance in juvenile chinook salmon. J. Aquat. Animal Health 15:1-12.

Johnson, J. H., A. A. Nigro, and R. Temple. 1992. Evaluating enhancement of Striped Bass in the context of potential predation on anadromous salmonids in Coos Bay, Oregon. North American Journal of Fisheries Management 12: 103-108.

Karchesky, C. M. and D. H. Bennett. 1999. Dietary overlap between resident fishes and juvenile salmonids in Lower Granite Reservoir, Idaho-Washington. *In* ODFW and NMFS. 1999. Management Implications of Co-occurring Native and Introduced Fishes. Proceedings of the Workshop. October 27-28, 1998, Portland, Oregon.

Kareiva, P., M. Marvier, and M. M. McClure. 2000. Recovery and management options for spring/summer chinook salmon in the Columbia River Basin. Science 290: 977-979.

Krueger, C. C. and B. May. 1991. Ecological and genetic effects of salmonid introductions in North America. Canadian Journal of Fisheries and Aquatic Sciences 48 (Suppl. 1): 66-77.

Levin, P. S., S. Achord, B. E. Feist, and R. W. Zabel. 2002. Non-indigenous brook trout and the demise of Pacific salmon: a forgotten threat? Proceedings of the Royal Society of London B 259: 1663-1670.

Maret, T. R., C. T. Robinson, and G. W. Minshall. 1997. Fish assemblages and environmental correlates in least-disturbed streams of the upper Snake River basin. Transactions of the American Fisheries Society 126: 200–216.

Mantua, N. J. and S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069-1079.

McElhany, P., M. H. Ruckelshaus, M. J. Ford, T. C. Wainwright, and E. P. Bjorkstedt. 2000. Viable salmon populations and the recovery of evolutionarily significant units U.S. Dept. Commerce, NOAA Tech. Memo. NMFS-NWFSC-42, 156 p.

Mesa, M. G., T. .P. Poe, A. G. Maule, and C. B. Schreck. 1998. Vulnerability to predation and physiological stress responses in juvenile chinook salmon *(Oncorhynchus tshawytsch*a) experimentally infected with *Renibacterium salmoninaru*m. Canadian Journal of Fisheries and Aquatic Sciences 55: 1599–1606.

Nickelson, T. 2003. The influence of hatchery coho salmon (*Oncorhynchus kisutch*) on the productivity of wild coho salmon populations in Oregon coastal basins. Can. J. Fish. Aquat. Sci. 60:1050–1056.

NMFS (National Marine Fisheries Service). 2000. Predation on Salmonids Relative to the Federal Columbia River Power System.

NRC (National Research Council). 1996. Upstream: Salmon and society in the Pacific Northwest. National Academy Press, Washington, D.C.

Parker, I. M., D. S. Simberloff, W. M. Lonsdale, K. Goodell, M. Wonham, P. Kareiva, M. H. Williamson, B. Von Holle, P. B. Moyle, J. E. Byers, J. E., and L. Goldwasser. 1999. Impact: toward a framework for understanding the ecological effects of invaders. Biological Invasions 1: 3-19.

Pearsons, T. N., and C. W. Hopley. 1999. A practical approach for assessing ecological risks associated with fish stocking programs. Fisheries 24(9):16–23.

Poe, T. P., M. G. Mesa, R. S. Shively, and R. D. Peters. 1994. Development of biological criteria for siting and operation of juvenile fish bypass systems: Implications for protecting juvenile salmonids from predation. Pages 169-176, *in* Fish Passage Responsibility and Technology. Symposium Proceedings. American Fisheries Society Annual Meeting, 1993. Portland, Oregon.

Reno, P. W. 1998. Factors involved in the dissemination of disease in fish populations. Journal of Aquatic Animal Health 10: 160–171.

Rieman, B. E., R. C. Beamesderfer, S. Vigg, and T. P. Poe. 1991. Estimated loss of juvenile salmonids to predation by northern squawfish, walleyes, and smallmouth bass in John Day Reservoir, Columbia River. Transactions of the American Fisheries Society 120:448-458.

Waknitz, F. W., T. J. Tynan, C. E. Nash, R. N. Iwamoto, and L. G. Rutter. 2002. Review of potential impacts of Atlantic salmon culture on Puget Sound chinook salmon and Hood Canal summer-run chum salmon evolutionarily significant units. U. S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-53, 83 p.

Waples, R.S. and Drake, J. 2004. Risk/Benefit Considerations for Marine Stock Enhancement: A Pacific Salmon Perspective. In: *Stock Enhancement and Sea Ranching Developments, Pitfalls and Opportunities.* 2nd Ed. Leber, K.M., Kitada, S., Blankenship, H.L., and Svasand, T. Eds, pp. 260-306. Blackwell Science, Oxford.

8. How is the biology of individuals (e.g., physiology and behavior) linked to fish condition and salmon population VSP characteristics?

Background

The biology of individual salmon affects the abundance, productivity, spatial structure and diversity of the species/stock by the physiological adaptive processes that dictate fitness of individuals. Population abundance depends on survival of individuals and successful reproduction, which in turn relies on individual ability to accumulate energy for basic metabolic needs, growth, juvenile development (smolting), disease resistance, appropriate behaviors (e.g., predator avoidance) and maturation. Productivity depends on survival to successful maturation at appropriate age, size, season, fecundity, egg size, and gamete quality. Spatial structure depends on individual exploitation and survival in a range of habitats, including the ability to imprint and successfully home to spatially distributed natal streams. Diversity depends on individual life history plasticity, including timing of emergence, age and timing of smolting, migration timing, and age and timing of reproductive maturation, among other factors. Environmental factors (the physical, biological and chemical habitat condition, including temperature, photoperiod, food availability, food composition, density, and toxicants) influence the physiology of individuals to regulate essentially all adaptive processes both in the wild and in conservation hatcheries. However, we presently have only a rudimentary knowledge of the physiological mechanisms regulating fish survival and adaptive scope in response to fluctuating environmental conditions.

Although the physiological phenotype of salmonid species/stocks depends on their genetic makeup (local adaptation), the heritabilities of many key life history attributes, e.g., age of maturation, are below 0.5, which means phenotypic variation is largely dependent on environment.

Policy Implications

Recovery plans must identify specific actions to recovery species. Among those actions are assessing and improving environmental conditions. A better understanding of the mechanisms by which environmental factors affect individual fish will help guide evaluating and improving habitat, hydro and hatchery practices. Understanding the biological condition of individuals within a population will provide insight into why populations may be growing or declining, and dictate the range and priority of actions to sustain viable populations. Research results will be used by federal and state regulatory agencies and tribes.

Current Understanding

Physiological research on salmon survival, energetics, growth, development, migration and reproduction has shown clearly that environmental conditions regulate all of these processes (DeGroot et al., 1995; Physiological ecology of Pacific salmon). Most physiological studies of salmon have been done in the controlled conditions of laboratories and hatcheries, and only a few were conducted on fish in natural environments (see, for example, Beckman et al., 2000). We know in general many of the environmental effects on physiological processes, for example, studies on salmon growth and bioenergetics have identified minimal and optimal levels of energy intake (dietary ration and composition) for survival and growth for most salmonid species. Growth is highly dependent on diet and temperature, with seasonal growth also influenced by photoperiod. Growth rate influences fish development and sexual maturation. In general, rapid juvenile growth advances the occurrence of smolting and downstream migration, whereas slow growth delays these processes. For example, faster growing Atlantic and spring Chinook salmon and steelhead will smolt several months to one year earlier than slower growing counterparts. For some species of anadromous salmonids (spring Chinook salmon), rapid growth during smolting may enhance downstream migration of smolts and survival to adult stage. Growth rate also influences the age and timing of reproductive maturation. High growth rates after emergence may enhance male maturation within their first year. In general high growth during the year advances the age at reproductive maturation. Environmental factors including fish density and water temperature affect stress levels and onset of disease. There are a ranges of measures available to assess individual fish health and disease, and knowledge on fish immune systems and disease transmission is rapidly advancing. Finally, we are learning more about critical times and mechanisms responsible for homing imprinting of juveniles and homing behavior of adult salmon, which are critical for the spatial distribution of salmon.

Although detailed studies of molecular mechanisms responsible for mediating environmental effects on physiological and behavioral processes are expanding, there is a great deal more to be learned about lethal and sub-lethal effects. Fortunately, the growing information residing in salmonid genome and expressed sequence tag (EST) databases and the development of high-capacity gene expression microarrays for fish puts us on the threshold for a quantum leap in our ability to measure and understand the physiological condition of individual salmon. With continued effort in this area, assessment of physiological condition and behavior of individuals should be a valuable tool in assessing population viability.

Key Research Gaps

Although our general knowledge of salmonid physiology is probably more advanced than for any other fish species, major gaps exist in growth, development, reproduction, stress and disease resistance, immunology, toxicology, imprinting, homing and behavior. We need to learn more about basic physiological mechanisms on the molecular level to better understand these processes and develop better tools to measure physiological condition of fish in the wild and in captivity. We need to develop a broader range of physiological baselines for healthy individuals in healthy populations to better characterize the range of acceptable conditions and identify problems. For example, we know that some degree of egg retention or unfertilizable eggs of spawned females may be normal in captive populations, but we do not have very good information on how common this is in the wild. We know that life history plasticity in Chinook salmon for example, results in some degree of male maturation from ages zero through five, but we know neither the normal range in age of maturation in wild fish, nor how year-to-year environmental variation affects maturation. We know that homing to natal streams can be very close to 100%, but straying does happen, more so in some populations than in others. We don’t know whether different straying rates may be due to “errors” in imprinting or homing, or due to unsuitable spawning habitat in the natal stream. We know that some level of disease organisms, e.g., Renibacterium salmoninarum, is common in wild and captive salmon populations. However, we don’t know what is an acceptable level, or whether some populations are more resistant than others.

Finally, in addition to knowing more about basic physiological mechanisms and characterizing normal and abnormal populations, we need to know how to prioritize risks associated with various types of physiological/behavioral differences. Are inappropriately high water temperatures affecting growth rates and disease resistance in the spring more of a threat to abundance and productivity than inappropriately high water temperatures in the autumn delaying migration and reproductive maturation?

The major focus areas in physiology and behavior affecting abundance, productivity, spatial structure and diversity are listed below along with associated sets of measures.

Early development (morphogenesis, organogenesis, teratogenesis)

Nutrition and growth (primary production in streams or estuaries, prey abundance, feeding behavior, growth rate, condition factor, asymptotic size, age at maturity,).

Physiological stress (behavioral thermoregulation, oxidative stress, hsp induction).

Mortality from infectious disease (immunocompetence, pathogen load and prevalence of symptoms).

Smoltification and osmoregulation (gill Na+/K+ ATPase activity, thyroxin levels, seawater tolerance).

Migratory behavior (selection of juvenile rearing habitat, imprinting, adult homing behavior).

Reproductive success (selection of spawning habitat, courtship behavior, redd construction, egg size, numbers of eggs produced, eggs fertilized, or eggs hatched).

Behavioral ecology (habitat use, competition, predation, availability of shelter, predator detection, predator avoidance behaviors).

It is important to note that these parameters can be highly interdependent. For example, in the case of infectious disease, pathogens and their hosts usually evolve towards and reach equilibrium, as the survival of the pathogen - at least the obligate ones - depends on the survival of the host. Each of the other parameters of fish health or condition can tip the pathogen-host balance. For example, growth, stress, and smoltification are all stressors that can directly impact immunocompetence (which can range from non-specific cellular immunity to specific cellular or humoral immune function). Predation and injury can circumvent normal barriers to infection, and migratory behaviors can bring immuno-“naive” fish into contact with novel pathogens. This strongly emphasizes the need for collaborative, interdisciplinary research

Literature Cited

Beckman, B.R., D.A. Larsen, C. Sharpe, B. Lee-Pawlak, C.B. Schreck, and W.W. Dickhoff. 2000. Physiological status of naturally reared juvenile spring chinook salmon in the Yakima

River: Seasonal dynamics and changes associated with smolting. Trans. Am. Fish. Soc. 129:727-753.

Groot, C., L. Margolis, and W.C. Clarke. 1995. Physiological Ecology of Pacific Salmon. UBC Press, Vancouver, Canada. pp.

Table 1.

Research area	**Abundance**	**Productivity**	**Spatial Structure**	**Diversity**
Early development	x	x		x
Ntrition and growth	x	x		x
Physiological stress	x	x		
Mortality from infectious disease	x			
Smoltification and osmoregulation	x		x	x
Mirgratory behavior	x	x	x	x
Reproductive Success	x	x	x	x
Behavioral ecology	x	x	x	x

III. SCIENCE IN A DECISION FRAMEWORK

9. How does incorporating uncertainty about future environmental conditions into scenarios assessing the cumulative effects of recovery actions on the VSP characteristics of a population affect predictions of salmon population response?

Background

Our ability to predict Pacific salmon responses to proposed recovery actions is affected by numerous forms of uncertainty, limiting our capacity to discriminate among recovery alternatives. Uncertainty about future trends in climate, land use, and other factors that affect salmon populations makes accurate predictions of future salmon population sizes difficult. The high degree of natural variability and cyclicality in salmon populations complicates the task of predicting future salmon numbers and impedes efforts to communicate the results of our work to the public.

In systems characterized by high levels of uncertainty and uncontrollable variability, scenario planning provides a mechanism for developing robust conservation strategies (Peterson et al. 2003). The fundamental idea behind scenario planning is that, when future conditions are unpredictable, it is wise to explore the implications of a wide range of possible future conditions (scenarios). In its most comprehensive form, scenario planning involves the development of multiple descriptions of alternative futures that project substantially different trends in important system drivers into the future. The response of the variable(s) of interest (e.g., salmon population size) to each future scenario is then modeled. Ideally, scenarios are developed by a small but inclusive group of policymakers, scientists and stakeholders (Greeuw et al. 2000). Ultimately, the development of useful scenarios depends upon our ability to identify the major drivers in a system.

Policy Implications

Scenario planning can be used to identify conservation strategies that are robust to different sets of future conditions and to identify signals that might serve as advance indicators of which future path we are actually on. Scenario approaches, with their emphasis on conditionality, generally lead to the development of contingent strategies (i.e., if A happens, do X; if B happens, do Y) that should increase the speed with which we can respond to changing conditions. Much of the scenario planning literature emphasizes that scenarios should not simply represent a continuation of current trends but should include surprises (i.e., unlikely and extreme events). The inclusion of surprises provides the broadest basis for developing contingent response strategies, but, since scenario planning efforts generally create only three or four scenarios, identifying the types of surprises and extreme events to include requires careful thought.

Less comprehensive scenario-based approaches can also be useful. Scenarios that extrapolate trends of climate, land use change, exotic species invasions, and other forms of change into the future, while not viewed as true scenarios by some (e.g., Greeuw et al. 2000), can still provide insight into the impacts and interactions of those factors and allow a substantially more powerful analysis than those that assume static future conditions. In addition, these types of projections can serve as the basis for ecological forecasts: probabilistic assessments of future conditions (Clark et al. 2001).

A comprehensive approach to scenario development could involve TRT scientists, policymakers and stakeholders collaborating to develop a handful of alternative futures for a watershed or region. Collaborations between TRT scientists and other academic and agency scientists could yield scenarios of climate change, changes in local species assemblages, and land use change, given different assumptions about future trends in CO_2 levels, species movements, and population growth. Scenario modeling may be especially helpful in providing insight into the cumulative effects of several different forms of environmental change.

Some examples of possible scenario planning applications include:
(1) Climate
Numerous climate change scenarios have been developed over the past decade using at least eight different global climate models that project the climatic effects of different rates of change in atmospheric CO_2 concentrations. Different climate models predict a wide range of different temperature and rainfall patterns for the northwestern U.S. (Nakicenovic and Swart 2000; National Assessment Synthesis Team 2001), and could be used as the basis for the creation of alternative climate scenarios.

(2) Ocean conditions
Ocean conditions fluctuate on a variety of temporal scales, but, for Pacific salmon, the most important appears to be the Pacific Decadal Oscillation (PDO), which shifts phase on a 20- to 30-year cycle. Different scenarios of change between PDO phases could be incorporated into salmon population models. Global climate models currently do not model salmon-relevant ocean conditions well (Mote et al. 2003), so scenarios that incorporate the effect of climate change on ocean conditions are, at present, difficult to generate.

(3) Land use change
Numerous land use change projections have been developed (e.g., by county governments or programs such as the Willamette Valley Futures project) that could be used as the bases for land use change scenarios. Also, efforts to model the growth of urban areas (e.g., UW's UrbanSim project) may produce useful projections of land use change under different assumptions about the future that can then be tied, through the use of hydrology models, to variables such as stream flow and temperature that are relevant to salmon population dynamics.

(4) Species interactions
Changes in the distribution of predators, prey, and competitors—both native and exotic—clearly have the potential to affect salmon populations (see question 6), and scenarios could be used to examine the potential impacts of species introductions or extinctions on salmon populations. In general, quantitative data on the effect of species interactions on salmon population dynamics are lacking, and this will be an important avenue for further study.

(5) Everything else
Many other issues related to salmon population viability are amenable to scenario planning. Scenarios incorporating different hatchery management decisions, harvest regimes, dam building

or removal and many other management actions, as well as more extreme events (e.g., the eruption of Mt. Rainier, an oil spill in Puget Sound) could yield important insights into the potential consequences and robustness of management actions.

Scenario planning offers a way to incorporate strategies for adapting to change into projections of future conditions (Clark et al. 2001). For instance, an investigation of potential climate change impacts could include scenarios in which dam releases are altered either to benefit fish or to accommodate increasing water demand from a growing human population. Such scenarios could also include new reservoir construction to mitigate warming-related impacts on the water supply, or adaptive responses by the fish themselves. Scenarios that bracket the extremes of plausible future conditions are likely to provide the greatest insight into salmon population vulnerabilities and to allow the identification of robust conservation strategies for an uncertain future.

Space and Time Scales

Scenario planning can be conducted at virtually any spatial or temporal scale. Most applications of scenario-based approaches to environmental issues have been implemented at very large spatial scales (e.g., examinations of the implications of global climate change or national economic policies). Only recently have scenario-based approaches been applied to local and regional conservation issues. In one of the few applications so far, the implications of three regional development scenarios were studied for the 5000 km^2 Northern Highlands Lake District of Wisconsin (Peterson et al. 2003). A different approach is being applied by the ForestERA project (Hampton et al. 2003), which focuses on forest management issues in ponderosa pine forests in northern Arizona and New Mexico. Rather than design specific scenarios in advance, ForestERA scientists developed GIS-based decision-support tools that allow stakeholders, in collaboration with project staff, to develop and model the outcomes of whatever scenarios of ponderosa pine forest management are of greatest interest to them. The temporal scale of scenario planning exercises rarely extends beyond 50 years because of the exponential increase in uncertainty about future conditions as the time scale increases.

Key Research Gaps

Over the past decade scenario planning, which was first developed in the business world, has begun to be applied to environmental issues, but the approach is still poorly developed, especially at the spatial scales relevant to salmon recovery planning. There are two different classes of questions that need to be addressed: (1) questions that need to be answered in order to implement scenario planning, particularly those related to the development of useful scenarios (referred to below as implementation questions) and (2) questions about the effects of future environmental change that can be answered through the use of scenario planning (research questions).

Implementation questions

- What are the key drivers of the system?
- What key drivers might become more or less important in the future?
- What are the potential future states of key system drivers?
- For what surprises is it most important to understand how the system will respond?
- What should be the role of science in scenario planning for salmon recovery?

To model the responses of salmon, as well as other species of interest, to future conditions, we need to know how salmon can be expected to respond to those conditions. The research gaps and modeling needs identified in questions 1-7 are, therefore, equally relevant to scenario planning efforts. While there will always be uncertainty about the future, research that improves our understanding of the likely range of future conditions or attempts to quantify the degree of uncertainty associated with specific processes will increase our ability to create credible models with which to project possible outcomes of management actions. The identification of which of the factors important to salmon population persistence are likely to change the most is also essential. These efforts could include studies of the historical range of variation in variables of interest and modeling studies that attempt to predict the direction and magnitude of future change. We also need to assess the possibility that drivers that currently have the greatest impact on salmon populations may not be those that will have the greatest impact under altered environmental conditions. In addition, it will be important to identify potential surprises that have the capacity to have widespread impacts on salmon populations so that their effects can be incorporated into the development of future scenarios.

Scenario planning can be implemented in a number of different ways, ranging from a highly inclusive approach that involves a wide range of stakeholders in scenario development and evaluation to a small research group concocting and analyzing scenarios of their own devising. Scenarios can be explicitly stated at the outset of the process, with scientists' role then being to apply models to each scenario to determine its outcome for the variables of interest, or scientists can focus on developing tools that will allow policymakers and stakeholders, with some guidance and technical assistance, to develop and assess their own scenarios. Scenario modeling outcomes can be filtered through an optimization algorithm (e.g., question 10) or presented in a relatively raw form to decision-makers to be incorporated into the political decision-making process. It is likely that different approaches will be most appropriate to different questions and management issues. Because the application of scenario planning approaches to small- and mid-scale conservation problems is still relatively new, an important research objective will be to assess what approaches to scenario development and evaluation are most effective for issues related to salmon ESU conservation.

Research Questions

- How can salmon populations be expected to respond to future environmental conditions?
- How will different form of environmental change interact with each other to affect VSP characteristics?
- How will future environmental conditions interact with the impacts of hatcheries, dams, harvest, and habitat to affect VSP characteristics?
- How robust are proposed conservation actions to different assumptions about future conditions, and what contingencies should we prepare for?

Future environmental change may affect salmon populations directly, or effects may be indirect through interactions with other stressors. Scenario planning efforts thus need to assess both direct effects and the potential for interactions among different forms of environmental change. The effectiveness of conservation and management actions may be contingent on future conditions, and understanding how different management strategies may be affected by long-term change is likely to improve our ability to develop effective conservation strategies. Conservation actions that are effective under a wide range of future conditions are likely to be preferable to those that require a narrow range of environmental conditions in order to succeed, and scenario planning exercises should seek to identify robust strategies. Plans for habitat restoration and enhancement incorporating flexible strategies that are contingent on the trajectory of future change are more likely to succeed, and the identification of suites of actions that are appropriate to different future conditions should be a priority for scenario planning efforts.

Literature Cited

Clark, J. S., et al. 2001. Ecological forecasts: an emerging imperative. Science 293:657-660.

Greeuw, S. C. H., M. B. A. van Asselt, J. Grosskurth, C. A. M. H. Storms, N. Rijkens-Klomp, D. S. Rothman, and J. Rotmans. 2000. Cloudy crystal balls: an assessment of recent European and global scenario studies and models. Environmental Issues Series #17. European Environment Agency, Copenhagen.

Hampton, H. M., Y. Xu, J. W. Prather, E. N. Aumack, B. G. Dickson, M. M. Howe, and T. D. Sisk. 2003. Spatial Tools for Guiding Forest Restoration and Fuel Reduction Efforts. Proceedings of the 2003 ESRI International User Conference.

Mote, P. W. et al. 2003. Preparing for climate change: the water, salmon, and forests of the Pacific Northwest. Climatic Change 61:45-88.

Nakicenovic, N. and R. Swart, eds. 2000. Special Report on Emissions Scenarios. Cambridge University Press, Cambridge, UK.

National Assessment Synthesis Team. 2001. Climate change impacts on the United States: the potential consequences of climate variability and change. Cambridge University Press, Cambridge, UK.

Peterson, Garry D., G. S. Cumming, and S. R. Carpenter. 2003. Scenario planning: a tool for conservation in an uncertain world. Conservation Biology 17:358-366.

10. What monitoring is necessary to detect population and ESU status and the effects of recovery actions on the VSP characteristics of a population?

[under development]

11. How does integrating biological and economic information in an evaluation of the effect of suites of recovery actions on the VSP characteristics of a population or ESU alter the prioritization of impacts?

Background

A number of potential salmon recovery actions for listed Pacific salmonids already have been identified through various threats and limiting factors analyses. These analyses tend to tend result in long “laundry lists” of potential actions, sometimes ranked by a single attribute, such as expected change in salmon abundance. Deciding which actions to take to recover salmon will involve consideration of many more factors than a single attribute. Salmon recovery planning must integrate analyses on all the potential population threats to make decisions on recovery action priorities. Evaluating the relative value of a specific action involves not only predicting the biological response, but also consideration of social and economic costs and benefits. Identifying a management program that includes actions addressing all threats that simultaneously have a high probability of achieving biological or harvest goals, maximize economic and societal benefits, and minimize economic and social costs can be extremely problematic, given uncertainty in links between actions and biological response or social and economic costs.

Potential recovery actions for Pacific Salmon include freshwater habitat restoration or preservation, changes to harvest and hatchery management, exotic species control, estuarine habitat enhancement and restoration and alterations to large-scale hydropower dams. Actions in each of these areas have variable and often uncertain biological potential to improve salmon population status. Equally importantly, actions in each of these areas have variable impacts on societal goals as diverse as tribal and commercial harvest, electric power generation, agricultural production and recreational opportunities. Nevertheless, it is the task of recovery planning groups for listed salmon ESUs to identify and implement suites of actions that will lead to a persistent ESU. Such actions must not only be biologically defensible; they also must be socially, politically and logistically supported so that implementation of recovery measures can occur.

Developing recovery plans in this situation is hampered not only by uncertainty in the magnitude of expected response, but also by challenges in considering biological benefits, economic costs and societal benefits jointly in the decision-making process. A formal framework that incorporates uncertainty in biological and economic response while seeking to evaluate the relative costs and benefits of different suites of actions transparently is thus a critical element of effective recovery planning. Existing efforts to incorporate these myriad effects are rare, and those that do exist are limited to economic and biological analyses of one action class at a time (e.g., USACE 2000).

Key Question

Based on an evaluation integrating the expected bio-physical response, societal goals and societal constraints associated with potential actions addressing all threats, what is the “best” suite of actions that should be undertaken to recover a specific salmon population or ESU?

Policy Implications

This research question operates at the interface between science and policy. The analysis will incorporate scientific information on the predicted bio-physical responses caused by potential actions in addition to policy considerations of societal and economic costs and benefits. Although scientists can provide analyses inputs regarding prediction bio-physical response, and help to develop the specific framework/models for evaluation, the societal/ecomomic inputs to the analyses would need to be provided by managers and policy makers. The results of the analysis, identification of candidate suites of recovery actions with a high likelihood of both biological and societal success, can be used to inform recovery planning. Although no single “tool” or analysis should be relied on as the sole means to make the difficult management decisions needed for recovery planning, a thorough analysis can provide a systematic and transparent framework for considering and evaluating potential suites of recovery actions. Since deciding among recovery actions is one of the most challenging and challenged aspects of salmon recovery planning, this research should be very valuable to policy makers.

Potential Approach

Decision support tools provide one means of systematically incorporating multiple parameters as well as uncertainty in those parameters in the evaluation of alternative management scenarios (Clemen 1996). These multiple parameters can even span several disciplines; a single decision support model can incorporate scientific, economic, legal and other considerations. Importantly, when well-constructed and documented, decision support tools ensure transparency in the decision process, by requiring that the weightings or importance of difference factors, or the interactions between factors are clearly outlined (Ludwig et al. 1993) Although these well-constructed and documented models can be challenging to create, they have been used in several conservation and fisheries applications (Hilborn 1997, Punt and Hilborn 1997, Starr et al. 1997, Shea et al. 1998, Burgman et al. 2001).

Any decision support approach to selecting the "best" suite of recovery actions will likely involve the following steps, as shown in **Figure 1**:

1) Describing the predicted effects of potential actions. In this step, actions aimed at salmonid recovery in all management arenas will be systematically identified, and their anticipated biological, economic and social results characterized in a consistent "currency"
2) Identifying goals. This step requires the desired outcome (goals) to be clearly laid out. In the case of ESA-listed salmonids, goals are likely to be articulated as recovery targets, achieved with some certainty.
3) Identifying "rule sets" or "constraints." In this step, the conditions under which stakeholders desire the goals to be met are described.
4) Application of an optimization algorithm to rank suites of actions. Our optimization algorithm will functionally filter alternative suites of actions by their ability to meet the desired goals, given the outlined constraints. All possible combinations of actions will be evaluated.

We describe each of these steps more fully below.

Table 1: Example rule sets for prioritizing salmon recovery actions.

	Biological	Social	Economic
Rule Set 1	Minimum salmon viability criteria	Maximize tribal harvest Maintain sport fisheries at moderate levels	Maximize electrical generation Minimize total cost outlay (i.e. not including lost revenues)
Rule Set 2	Minimum viability criteria; maximizing certainty of achieving criteria	Allow some tribal harvest; Maximize "sector equity" in distribution of actions	Do not allow electrical generation to fall below x; overall cost of habitat actions cannot exceed y
Rule Set 3	Minimum viability criteria	etc.	etc.

Description of Action Effects

Individual actions to recover salmon have been described as addressing one or more of the "4-Hs" of potential threats to salmon population status: habitat, hydrosystem, harvest and hatcheries. Actions may also affect factors that are not so alliterative, such as exotic species or pathogens. Each action has a large number of attributes that are important to consider when selecting among different possibilities for inclusion in the recovery plan. The sheer number of possible actions and their predicted effects are part of the reason a systematic selection process has remained elusive. We can partition the attributes of individual actions into three major categories: 1) biological, 2) economic and 3) social. Within each of these categories are a number of sub-categories.

The biological attributes include population characteristics of the focal species for which recovery analyses are being conducted. The Viable Salmonid Population (VSP) approach adopted by NOAA Fisheries describes four key parameters related to salmon viability (i.e., abundance, productivity, spatial structure and diversity; McElhany et al. 2000). Analyses in support of making good recovery decisions must be able to predict the response for each of these population attributes for every potential action. There is a great deal of uncertainty associated with the biological response to any given action, and this uncertainty itself is another attribute that is important to capture in the results. Furthermore, many of the action effects are dependent on what other actions are included in the suite of recovery projects. For example, the effects of hatchery management actions often depend on harvest actions, and stream bank restoration projects can depend on hydrosystem operations in regulated rivers. These interactions add complication to predictions, but they are important to include because of their effects on selection of an acceptible suite of actions for achieving goals. Biological attributes not strictly related to population viability also have been identified as part of overall recovery goals in some planning areas. These other attributes include goals for a harvestable surplus, and reducing the degradation of ecosystem processes. Finally, the location and spatial extent of the biological response to a proposed action are important factors for deciding on an acceptable suite of actions, as are the time lags expected for any biological response.

Finding an “optimal” program of conservation actions entails gauging the effects of that program on a variety of biological, economic, and social indicators. In classic benefit-cost analyses, all of these indicators are expressed in a single metric - monetary value (Zerbe and Dively 1994) The optimization process then finds the program that maximizes the net benefits of conservation, as measured by that metric.

This approach is rarely practical and frequently generates considerable opposition on other grounds, as expressing all values in monetary terms is often viewed as inappropriate (Sagoff 2000; Bromley 1990). The key idea underlying our approach is to use metrics appropriate for the type of indicator. While this precludes estimating the net benefits of each action, this approach nevertheless is capable of providing a simple, intuitive method for setting conservation priorities: Give highest priority to those actions that have greater ecological effects relative to the economic and social impacts of producing those effects.

Just as there is uncertainty in estimating the biological response resulting from an action, so there is uncertainty about the economic and social impacts of an action. For example, while general cost estimates exist for classes of habitat actions for Pacific salmon recovery, these estimates present a range of costs applicable to a specific action (Evergreen Funding Consultants, 2003). Moreover, the relations between these impacts and an action may vary spatially, as regional economic and social factors affect their magnitudes. These sources of variation must be articulated in the results from a decision support analysis.

There have been some attempts in resource management to put the societal impacts in the same currency as the economic analysis (i.e. dollars). Others have argued (and we agree) that the societal issues should be considered separately. Societal costs include such factors as lost native cultural values, aesthetic value, lost opportunities for education, and political costs such as the difficulties in implementing particular actions. If an action has high biological potential and low cost, but legislation prevents implementation of the action, such an action will not likely be included among the highest ranked solutions. Pulling together the information needed to evaluate every action is a challenging task and will involve biologists, physical scientists, economists, social scientist, resource managers and stakeholders.

Desired Outcomes, Goals and Constraints Yield a Rule Set

Once the likely biological, social and economic responses of actions have been characterized, a set of goals and constraints that describe the desired outcome is required. These goals provide the basis for sorting through all possible combinations of actions. For example, a relatively simple rule set might be to simultaneously achieve minimum biological recovery criteria, not exceed some maximum dollar amount, and to prioritize suites of actions by expected level of tribal harvest. The rule sets can include any of the attributes described for each action as the elements of a decision. For example the rule sets could include rules for allocation of economic costs among stakeholders, minimization of time-lags to recovery, prioritization for certain societal needs, or maximizing the certainty of a particular biological response. Policy makers and stakeholders should generate rule sets for evaluations so that their decisions can be better informed by tradeoffs among the three key constraints.

Potential Algorithms for Selecting Suites of Actions

A number of approaches can be taken to evaluate the suites of potential actions relative to the rule set and to prioritize the actions relative to how well they meet the rule set requirements. In Figure 1, potential suites of actions are ranked from "high" to "low" as a function of how well they meet the requirements of the rule set. If the number of potential action suites is small and the rule set is relatively simple, it might be possible by brute computational force to examine every possible combination of action suites. However, when the rule set is more complex and there are a large number of potential actions (as is the case in most salmon recovery decisions), a search algorithm that explores the action space is needed to identify likely action combinations. A number of approaches exist to perform such explorations, and one early task in this project is selection of the appropriate "optimization" method.

The problem of selecting suites of potential actions is analogous to the problem of identifying sites for conservation protection. Both problems involve the identification of the optimal set of items (either recovery actions or conservation sites) based on a number of constraints and goals. Simulated annealing is one approach that has been applied to complex conservation siting problems that could be appropriate for the selection of recovery actions (e.g. Andelman and Willig 2002). Simulated annealing does not examine every possible combination of actions (there are simply too many), but rather finds sets of actions that meet the constraints and maximize relative to specified criteria. With this approach, an "irreplicability analysis" can be conducted to determine which actions occur in all or most of the acceptable action suites and conversely which actions never or hardly ever occur in any acceptable action suites (Noss et al 2002).

Another approach to decision support algorithms relies on a Bayesian framework (Pratt et al. 1996, Wade 2000). The Bayesian approach is very effective at incorporating the uncertainty in the analysis, but requires that values be expressed in terms of probabilities. This may lead to greater parameter estimation requirements, but a rich literature exists for analyzing decisions in a Bayesian context. Results from a Bayesian analysis are expressed in terms of outcome probabilities, which may be the most meaningful to managers.

It is possible in the rule set to have as many constraints as needed, but the optimization algorithms can only maximize or minimize by one action attribute at a time (or at least only attributes that are in a common currency). However, by combining separate analyses that maximize of minimize different attributes, an acceptable suite of attributes may be identified.

A decision support tool would be most effective if used by recovery planning groups consisting of stakeholders and members with the appropriate expertise in biology, economics, and resource management. Such recovery planning groups already are engaged in many areas of the Pacific Northwest, and they are eager for additional analytical support to help inform their difficult policy decisions (e.g., www.sharedsalmonstrategy.org.).

Potential Pitfalls

The approach includes a key assumption that all of the various factors (e.g. biological response, societal goals, etc.) can be made explicit and to some extent quantified. Obtaining this explict information may not be cost effective, in terms of time, effort and money, relative to the value of the analysis. If the recovery planning processes are not a stage where these analyses can actually inform management decisions, they would be of limited utility.

Literature Cited

Andelman, S. J. and M.R. Willig. 2002. Alternative configurations of conservation reserves for Paraguayan bats: considerations of spatial scale. Conservation Biology 16(5) 1352-1363.

Bromley, D. W. 1990. The ideology of efficiency: Searching for a theory of policy analysis. Journal of Environmental Economics and Management 19: 86_107.

Burgman, MA, S. Ferson and HR Akcakaya. 1993. Risk Assessment in Conservation Biology. Chapman Hall, London.

Burgman, M.A., Possingham, H.P., Jasmyn-Lynch, A., Keith, D.A., McCarthy, M.A., Hopper, S.D., Drury, W.L., Passioura, J.A., and DeVries, R.J. 2001. A decision support protocol for setting plant conservation target areas. Conservation Biology. 15:603-616.

Clemen, R.T. 1996. Making Hard Decisions: An introduction to decision analysis. Duxbury Press. Pacific Grove.

Cooke, JG. 1995. The International Whaling Commission’s Revised Management Procedure as an example of a new approach to fisheries management. In: Blix, AS, L Walloe, O Ulltang (Eds.) Whales, Seals, Fish and Man. Elsevier, Amsterdam. Pp. 647-657.

Evergreen Funding Consultants. 2003. A primer on habitat project costs. Prepared for Shared Strategy by Evergreen Funding Consultants. Available at: www.sharedsalmonstrategy.org/files/PrimeronHabitatProjectCosts.pdf.

McElhany, P., M. Ruckelshaus, M. J. Ford, T. Wainwright and E. Bjorkstedt. 2000. Viable salmonid populations and the recovery of Evolutionarily Significant Units. NMFS-NOAA technical memorandum NMFS-NWFSC-42.

Haight, R. G., Cypher, B., Kelly, P. A., Phillips, S., Possingham, H. P., Ralls, K., Starfield, A. M., White, P. .J. and Williams, D. 2002. Optimizing habitat protection using demographic models of population viability. Conservation Biology 16:1386-1397.

Hilborn, R. 1997. Statistical hypothesis testing and decision theory in fisheries science. Fisheries 22 (10): 19-20

Huppert, Daniel D. 1999. "Snake River Salmon Recovery: Quantifying the Costs". Contemporary Economic Policy 17(4):476-491

Huppert, Daniel D., Annette M. Olson, Marc J. Hershman, Kate T. Wing and Caitlin M. Sweeney. 1998. "Socioeconomic Causes and Consequences of Coastal Ecosystems Change" Chapter 3 In McMurray, Gregory R., and Robert J. Bailey (eds.). Change in

Pacific Northwest Coastal Ecosystems: Proceedings of the Pacific Northwest Coastal Ecosystems Regional Study Workshop, August 13-14, 1996, Troutdale, Oregon. NOAA Coastal Ocean Program Decision Analysis Series No. 11. 342 p.

Huppert, Daniel D. 1996. "Risk Assessment, Economics, and Precautionary Fishery Management". Pp. 103-128 In Precautionary Approach to Fisheries Part 2: Scientific Papers. FAO Fisheries Technical Paper 350/2, Rome.

Huppert, D. and R. Fight. 1991. Economic Considerations in Managing Salmonid Habitats. Chapter 16 in W.R. Meehan (ed.) Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitat. American Fisheries Society Special Publication 19; Bethesda, Maryland.

Ludwig, D., R. Hilborn, and C. Walters. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. Science 260: 17/ 36.

Millner-Gulland, EJ, K. Shea, H. Possingham, T Coulson, and C. Wilcox. 2001. Competing harvesting strategies in a simulated population under uncertainty. Animal Conservation 4: 157-167.

Morgan, M. G. & Henrion, M. (1990). Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge University Press.

Noss, R.F., C. Carroll, K. Vance-Borland, G. Wuerthner. 2002. A multicriteria assessment of the irreplaceability and vulnerability of sites in the Greater Yellowstone Ecosystem. Conservation Biology 16(4) 895-908.

Pratt, J.W., H. Raiffa, R. Schlaifer. 1996. Statistical decision theory. MIT Press. Cambridge, MA.

Punt, A.E. and R. Hilborn. 1997. Fisheries stock assessment and decision analysis: the Bayesian approach. Reviews in Fish Biology and Fisheries. 7: 35-63.

Punt, A. and R. Hilborn. 2002. Bayesian stock assessment methods in fisheries. FAO Computerized Information Series (Fisheries) No. 12. 56 p.

Sagoff, M. 2000. Environmental economics and the conflation of value and benefit. Environmental Science and Technology 34: 1426-1432.

Shea, K., Amarasekare, P., Mangel, M., Moore, J., Murdoch, W. W., Noonburg, E., Parma, A., Pascual, M. A., Possingham, H. P., Wilcox, W. and Yu, D. 1998. Management of populations in conservation, harvesting and control. Trends in Ecology and Evolution 13:371-374.

Starr, P.J., Breen, P.A., Hilborn, R. and T.H. Kendrick. 1997. Evaluation of a management decision rule for a New Zealand rock lobster substock. Mar. Freshwater Res., 48: 1093-1101.

Tversky, A. & Kahneman, D. (1974). Judgment under uncertainty: heuristics and biases. Science 185, 1124-1131.

USACE, 2000. Lower Snake River juvenile salmon migration feasibility report and environmental impact statement (Final FR/EIS). Walla Walla District, Corps of Engineers, Department of the Army. http://www.nww.usace.army.mil/lsr/final_fseis/study_kit/studypage.htm

Wade, P.R. 2000. Bayesian methods in conservation biology. Conservation Biology 14(5) 1308-1316.

Westphal, M. I., Pickett, M., Getz, W. M. and Possingham H. P. 2003. The use of stochastic dynamic programming in optimal landscape reconstruction for metapopulations. Ecological Applications 13(2): 543-555.

Westphal, M.I. and Possingham H. P. 2003. Applying a decision-theory framework to landscape planning for biodiversity: Follow-up to Watson et al. *Conservation Biology* 17:327-329.

Zerbe, R.O. and D.D. Dively. 1994. Benefit_cost analysis: in theory and practice. HarperCollins College Publishers, New York.