INDEPENDENT SCIENTIFIC ADVISORY BOARD
& INDEPENDENT SCIENTIFIC REVIEW PANEL

Critical Uncertainties

for the Columbia River Basin Fish and Wildlife Program

ISAB/ISRP 2016-1
JANUARY 29, 2016

Independent Scientific Advisory Board
for the Northwest Power and Conservation Council,
Columbia River Indian Tribes, and
National Marine Fisheries Service

Independent Scientific Review Panel
for the Northwest Power and Conservation Council

851 SW Sixth Avenue, Suite 1100
Portland, Oregon 97204

Cover photos by Tony Grover and design by Eric Schrepel

ISAB and ISRP Contributors

- **J. Richard Alldredge, Ph.D.,** (ISRP Peer Review Group) Emeritus Professor of Statistics at Washington State University
- **Kurt D. Fausch, Ph.D.,** Professor of Fisheries and Aquatic Sciences, Department of Fish, Wildlife, and Conservation Biology at Colorado State University
- **Stanley Gregory, Ph.D.,** Professor Emeritus of Fisheries at Oregon State University
- **David Heller, M.S.,** Aquatic Habitat Management and Restoration Consultant, formerly Fisheries Program Leader for the Pacific Northwest Region, United States Forest Service
- **Wayne Hubert, Ph.D.,** Fisheries Consultant and Professor Emeritus at the University of Wyoming, Department of Zoology and Physiology
- **William Jaeger, Ph.D.,** Professor of Applied Economics at Oregon State University (also serves on IEAB)
- **Cynthia Jones, Ph.D.,** Eminent Scholar and Professor of Ocean, Earth, and Atmospheric Sciences; Director of the Center for Quantitative Fisheries Ecology; and A.D. and Annye L. Morgan Professor of Sciences at Old Dominion University, Virginia
- **R. Scott Lutz, Ph.D.,** Associate Professor of Wildlife Ecology, University of Wisconsin
- **Alec G. Maule, Ph.D.,** Fisheries Consultant and former head of the Ecology and Environmental Physiology Section, United States Geological Survey, Columbia River Research Laboratory
- **Katherine W. Myers, Ph.D.,** Research Scientist, Aquatic and Fishery Sciences, University of Washington (Retired)
- **Robert J. Naiman, Ph.D.,** Emeritus Professor of Aquatic and Fishery Sciences at University of Washington
- **Gregory T. Ruggerone, Ph.D.,** (ISAB Chair) Fisheries Scientist for Natural Resources Consultants
- **Laurel Saito, Ph.D., P.E.,** Director of the Graduate Program of Hydrologic Sciences at the University of Nevada Reno
- **Dennis L. Scarnecchia, Ph.D.,** Professor of Fish and Wildlife Sciences at University of Idaho
- **Steve L. Schroder, Ph.D.,** (ISRP Chair) Fisheries Consultant and former Fisheries Research Scientist at the Washington Department of Fish and Wildlife
- **Carl J. Schwarz, Ph.D.,** Professor of Statistics and Actuarial Science at Simon Fraser University, Canada
- **Desiree Tullos, Ph.D., P.E.,** Associate Professor at Oregon State University, Biological and Ecological Engineering Department
- **Thomas Turner, Ph.D.,** Professor of Biology and Associate Dean for Research at the University of New Mexico
- **Chris C. Wood, Ph.D.,** Former Research Scientist at the Pacific Biological Station, Fisheries and Oceans Canada, Nanaimo, British Columbia, Canada

ISAB Ex Officios and ISAB/ISRP Manager

- **Michael Ford, Ph.D.,** Director of the Conservation Biology Program at the Northwest Fisheries Science Center
- **Jim Ruff, M.S., P.H.,** Manager, Mainstem Passage and River Operations, Northwest Power and Conservation Council
- **Zach Penney, Ph.D.,** Fishery Science Department Manager at the Columbia River Inter-Tribal Fish Commission
- **Erik Merrill, J.D.,** Manager, Independent Scientific Review, Northwest Power and Conservation Council

Contents

Acknowledgements ... iii

Executive Summary ... 1

Preface: Review Charge, Approach, and Products ... 12

Part 1. A Revised Set of Critical Uncertainties ... 14

Review Process ... 14

Establishing Infrastructure Needed to Address Uncertainties ... 17

List of Critical Uncertainties by Theme ... 18

- Public engagement ... 18
- Human development ... 23
- Tributary Habitat ... 24
- Hydrosystem flow and passage operations ... 25
- Mainstem habitat ... 28
- Estuary, plume, and ocean ... 30
- Contaminants ... 32
- Climate change ... 35
- Non-native species ... 38
- Predation ... 39
- Fish propagation ... 43
- Harvest ... 46
- Population structure and diversity ... 48
- Monitoring and evaluation methods ... 52

Part 2. Summary of Progress toward Addressing 2006 Research Plan Critical Uncertainties ... 56

Review Process ... 56

Fish Propagation ... 58

Hydrosystem ... 77

Tributary and Mainstem Habitat ... 91

Estuary ... 97

Ocean ... 101

Harvest ... 104

Population Structure and Diversity ... 110

Climate Change ... 118
Contaminants ... 121
Non-Native Species ... 123
Human Development ... 129
Monitoring and Evaluation ... 132
Appendix A. Challenges for Prioritizing Uncertainties to Guide Management Decisions ... 139
Organizations, information, and decision making ... 140
A three-dimensional decision matrix ... 145
Implications ... 145
Appendix B. Guidance for Evaluating Progress ... 147
Appendix C. Guidance for Evaluating Criticality ... 148
Appendix D. ISRP and ISAB Comments on Annual Reports for Fish and Wildlife Program Projects with a Research, Monitoring, and Evaluation Work Element (*link to separate document*) ... 150
Literature Cited ... 151

Table of Programmatic Comments

Programmatic Comment 1. Improved coordination with land management agencies ... 22
Programmatic Comment 2. Water quality ... 34
Programmatic Comment 3: Water security ... 37
Programmatic Comment 4. Predators as part of the ecosystem ... 40
Programmatic Comment 5. Predator control ... 42
Programmatic Comment 6. Density dependence ... 43
Programmatic Comment 7. Brood tables ... 53

Acknowledgements

Numerous individuals assisted the ISAB and ISRP with this report. Their help is gratefully acknowledged. The ISAB Ex Officio members organized briefings, provided context, and commented on drafts: Jim Ruff, Mike Ford, Zach Penney, and Peter Galbreath (interim CRITFC Ex Officio).

We received many useful presentations that helped frame our review:

- Paul Lumley, Executive Director of the Columbia River Inter-Tribal Fish Commission (CRITFC) and ISAB Administrative Oversight Panel representative, gave an overview of CRITFC's Program. Bob Heinith and Romeo Wisco, CRITFC contractors, briefed us on the status and results of CRITFC's Climate Change Impacts Project.
- Tom Karier, Washington member of the Northwest Power and Conservation Council, gave us the Council's perspective on updating critical uncertainties and revising the research plan. Tony Grover, Fish and Wildlife Director, briefed us on the 2014 Fish and Wildlife Program and the role of adaptive management. Nancy Leonard and Patty O'Toole, Council staff, provided additional detail on the Program's research, monitoring, and evaluation (RM&E) approach and High Level Indicators (HLIs). Jim Ruff and John Fazio, Council staff, gave us an overview of hydrosystem operations.
- Mike Ford updated us on NOAA Fisheries Northwest Fisheries Science Center's 2016 status reviews, recovery plans, 2015 protected species program reviews, and recent research publications.
- Elena Nilsen, U.S. Geological Survey (USGS), presented on multi-agency efforts to improve the state of knowledge on toxics in the Columbia River Basin. Jen Beyer and Becca Scully, USGS, briefed us on the Pacific Northwest Aquatic Monitoring Partnership's efforts including regional RM&E, coordinated assessments, MonitoringResources.org, and MonitoringMethods.org.
- Brad Eppard, U.S. Army Corps of Engineers, gave an overview of the Corps' Anadromous Fish Evaluation Program (AFEP).
- Ben Zelinsky, Bonneville Power Administration (BPA) staff, briefed us on BPA's RM&E reform effort.

Ben, Katie McDonald, Brian Mercier, and Russell Scranton (BPA staff) helped define the list of Fish and Wildlife Program projects containing RM&E work elements and made the projects' annual reports available for our review through the CBfish website.

David Levine, ISRP technical assistant, and Jason Walters, ISAB intern from the University of Idaho Water Resource's doctoral program, assisted us for several months and facilitated work session discussions, took meeting minutes, and refined the research uncertainties database.

Special acknowledgement to Council staff for their assistance in this ambitious review. Kendra Coles assisted with meeting logistics and checked the report's references. Patty O'Toole, Jim Ruff, Nancy Leonard, and Lynn Palensky helped facilitate numerous meeting discussions on the progress of research toward addressing uncertainties and the criticality of the uncertainties; they skillfully provided context while eliciting the ISAB and ISRP members' independent opinions. Patty and Nancy also helped us input and manage information in the uncertainties database. Eric Schrepel created our annual report review and uncertainties databases, and he was always responsive to our many requests for changes.

Executive Summary

The 2014 Fish and Wildlife Program (hereafter Program) calls for the Northwest Power and Conservation Council to review ongoing research and revise the Program's Research Plan. The current Research Plan (Council Document 2006-3) lists 44 critical uncertainties, defined as "important knowledge gaps about resources and the functional relationships that determine fish and wildlife productivity in the Columbia River ecosystem." To help update the Research Plan, the Council asked the Independent Scientific Advisory Board (ISAB) and Independent Scientific Review Panel (ISRP) to reexamine these uncertainties and to recommend revisions after reviewing progress achieved by current research, monitoring, and evaluation projects within the Program.

Organization of the Full Report

Our full response to this request is organized in two parts. Part 1 presents 50 critical uncertainties organized under 14 themes. A rationale is provided for each uncertainty to explain its importance to the Program. Some of these critical uncertainties were revised from those in the 2006 Research Plan, and others are new. Part 2 presents an evaluation of the extent to which 187 ongoing Program projects (those with a research, monitoring, or evaluation component) have addressed, or could potentially address, the 44 critical uncertainties in the 2006 Research Plan. Appendix D to Part 2 provides a synopsis for each reviewed project. The synopsis indicates which of the 2006 uncertainties were directly or indirectly addressed by the project and includes brief comments about methods and results.

Overview of Current Projects

Within each theme, most projects addressed uncertainties only indirectly rather than directly (Fig. 1).

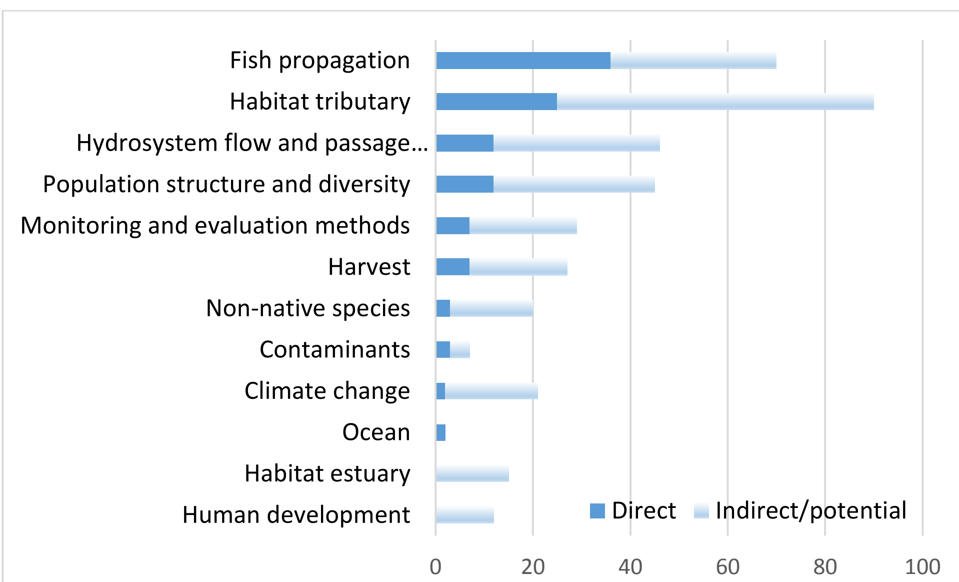


Figure 1. The number of Program projects that directly and indirectly examined uncertainties in the 2006 Research Plan by theme.

Thus, additional progress in addressing some uncertainties may be achieved by compiling, analyzing, and synthesizing information obtained from indirect studies. Other uncertainties, however, can only be resolved by focused funding to support more cohesive, controlled studies. In any case, the Council could improve communication and coordination among project teams by funding projects designed to synthesize information from diverse sources. The Council could also help convene workshops or symposia so that researchers working on similar uncertainties could share results, foster new approaches to research, and form broader partnerships. The Council could also require annual project reports to identify the uncertainties being addressed and document progress in resolving the uncertainties.

The distribution of projects across themes reflects the Program's past and current emphasis on habitat restoration and the use of artificial propagation to conserve and supplement natural populations, and to support fisheries. More projects directly addressed the tributary habitat and fish propagation themes than all other themes combined. A substantial number of Program projects also addressed uncertainties in the hydrosystem and population structure and diversity themes. The surprising number of projects associated with the population structure and diversity theme is largely attributable to the widespread application of genetic methods across a variety of species and locations and offers a special opportunity for integration and synthesis.

Other entities are leading research efforts in the Basin related to the themes of contaminants, climate change, and estuary habitat. Consequently, communication, coordination, and collaboration with these groups will be essential to incorporate their findings into the Program. Research to address uncertainties in the estuary and hydrosystem themes is largely supported by the U.S. Army Corps of Engineers through its Anadromous Fish Evaluation Program (AFEP), as well as fish passage research conducted at dams in the Willamette Subbasin. Although these projects are not directly funded by the Program, they are reviewed and implemented as part of Bonneville's reimbursable program and help to address Program uncertainties.

Only two Program projects were associated with uncertainties in the ocean theme. Understanding how conditions in the ocean affect growth and survival can help to guide and evaluate the effectiveness of efforts to restore anadromous species including eulachon, white sturgeon, and Pacific lamprey, as well as Pacific salmon and steelhead. No projects were directly associated with the human development theme; more research could strengthen projections of human impacts on fish and wildlife populations in the Basin.

Identification of New Uncertainties

The Council's draft uncertainties database contains nearly 700 questions that Council staff gleaned from over 130 regional reports and plans including relevant questions submitted during the 2014 Program amendment process. The ISAB and ISRP used this database to identify new uncertainties that should be included in a revised Research Plan. The complete list of uncertainties and judgments about their priority can be viewed in the online uncertainties database. Part 1 of the main report describes the 50 uncertainties judged to be of highest priority (i.e., critical). These critical uncertainties are grouped into 14 revised themes roughly corresponding to strategies listed in the 2014 Program; their order in our report does not reflect priority.

A key finding is that many of the questions listed in the Council's database are too broad for one or even a small set of research projects to address. Typically, research projects in the Basin are focused at or below the subbasin level and are conducted by scientists with expertise limited to one or two disciplines. What is often needed, however, are studies lasting for a decade or more that involve multiple subbasins and are conducted by integrated teams of professionals representing a diverse array of disciplines, such as fisheries, ecology, hydrology, modeling, and social sciences. Creating and supporting such teams will provide opportunities to make substantial progress in resolving many of the uncertainties described below. Strong and visionary leadership will be key to their success.

Critical Uncertainties[1] by Theme

Theme 1. Public engagement: The amended 2014 Program acknowledges public engagement as both a guiding scientific principle and a strategy for achieving the vision. Public engagement can improve the flow of information between the Program, its participants, and the general public through communication, consultation, and participation. The ISAB previously identified public engagement as one of four essential elements of a landscape approach (ISAB 2011-4). The other elements are (1) a scientific foundation based on principles from landscape ecology and the concept of resilience, (2) governance that allows for collaboration and integration, and (3) a capacity for learning and adaptation.

In this review, the ISAB and ISRP identified five uncertainties relevant to the landscape approach. The 2006 Research Plan did not include uncertainties specifically related to the landscape approach, so progress was not explicitly assessed in Part 2 of this review. However, the 2014 Program acknowledges the need for greater public engagement and set the stage for progress. Next steps in addressing this theme are to (1) support organizations that show promise for assisting with coordination, integration, and leadership toward achieving Program objectives and (2) engage the public in the development and evaluation of projections of future landscape change and other human impacts.

Theme 2. Human development: Fish and wildlife habitats will be affected by changes in society's use of land and other resources. However, most projections of fish and wildlife populations ignore future change in human population growth, fish and wildlife resource utilization, land development, and technological innovation that will influence the effectiveness of restoration efforts in the Basin. Federal and regional demographic projections provide a degree of confidence about population growth over the coming decades (doubling by 2100), but impacts will vary among locations, and it is difficult to predict changes in institutions and social preferences (e.g., willingness to pay for environmental protection). This uncertainty was identified as critical in the 2006 Research Plan and remains so. None of the projects reviewed in Part 2 directly addressed this uncertainty.

[1] Within this section only, critical uncertainties are called "uncertainties" to simplify the text.

Theme 3. Tributary habitat: A key assumption of the Program is that improvements in tributary habitats will mitigate for reduced survival and growth caused by hydrosystem operations and passage through multiple dams and reservoirs. Three uncertainties related to tributary habitat were identified (only slightly modified from the 2006 Research Plan). Briefly, these uncertainties are whether restoring or reconnecting tributary habitat to expand productive capacity can (1) mitigate for the loss of habitat capacity farther downstream or in the estuary or ocean, (2) provide benefits for wild populations in the face of high densities of hatchery and non-native fishes, and (3) increase resilience to buffer populations against extreme climate events and toxic contaminants.

More has been learned about the effectiveness of tributary restoration at the reach scale than about its aggregate effects on fish and wildlife populations at the watershed scale. Few projects have been conducted at the spatial scale required to resolve these uncertainties, and none has proceeded long enough to measure the full effects of restoration in the context of multiple stressors. Indeed, current methods may be inadequate to measure effects at the basin scale. The Integrated Status and Effectiveness Monitoring Program (ISEMP) and Columbia Habitat Monitoring Program (CHaMP) projects are exploring these issues, but many challenges remain. A key issue to be resolved is the extent to which population responses are determined by interactions between conditions in tributary habitat and conditions in mainstem, estuary or ocean habitat, fish passage through the hydrosystem, or other stressors such as non-native species and toxic contaminant~~s~~. Another important issue is the degree to which the protection or restoration of upslope habitat (much of which is in National Forests) can improve downstream water quality and aquatic habitat conditions in tributaries.

Theme 4. Hydrosystem and passage operations: The four uncertainties identified in the 2006 Research Plan remain relevant and were restated with minor revisions. Much progress has been made, but there is a continuing need for information about the impacts of hydrosystem flow and passage operations on all focal species (e.g., salmonids, white sturgeon, Pacific lamprey, and eulachon) to assess project compliance with BiOp-mandated targets and prioritize potential corrective actions. Of particular concern regarding salmonids are uncertainties about impacts on life history diversity due to variations in exposure to hydrosystem operations, the benefits of smolt transportation, and the effects of changing climate on fish passage through mainstem dams and reservoirs. Hydrosystem impacts on juvenile lamprey remain uncertain largely because of the lack of suitable tags.

A new (fifth) uncertainty concerns the feasibility of re-introducing anadromous runs of salmonids to areas that are now inaccessible due to dams. The key question is whether self-sustaining populations can be established above a high-head dam. Studies are planned above Chief Joseph Dam and in some tributaries to the Willamette and lower Columbia rivers. Successful re-introduction would likely require highly productive spawning and early rearing habitat to compensate for juvenile and adult mortality during passage through multiple dams and reservoirs, in addition to potentially unfavorable conditions in the ocean.

Theme 5. Mainstem habitat: The role of mainstem habitat in sustaining fish populations remains poorly understood. For example, fall Chinook and steelhead were once thought to rear exclusively in tributaries but have been reported migrating downstream to overwinter or rear in mainstem habitats. Generally, more research has been directed at understanding the impacts of habitat degradation in tributaries than the impacts of hydrosystem operations on mainstem habitat for salmonids and other focal species, such as Pacific lamprey, white sturgeon, and eulachon. Only one Program project has directly addressed the role of mainstem habitat, and progress has been slow.

Four uncertainties related to mainstem habitat were identified (including the single uncertainty about mainstem habitat identified in the 2006 Research Plan). These uncertainties emphasize the importance of understanding (1) the locations of thermal refuges in the mainstem that will be increasingly important as temperatures increase with climate change; (2) the extent to which the carrying capacity of mainstem habitats affects density-dependent responses, and hence, the assessment and management of focal species; (3) how carrying capacity in mainstem habitats might be maintained or improved by changing hydrosystem operations; and (4) how the availability of spawning and rearing habitat in the mainstem, especially above Bonneville Dam, affects the viability of white sturgeon.

Theme 6. Estuary, plume and ocean: Three uncertainties were identified for the estuary and ocean. The first uncertainty concerns specific factors that impact the growth, migration, maturation, and survival of focal fish species in the estuary, plume, and ocean. Some factors (e.g., avian predation on Chinook and steelhead smolts in the estuary) have been studied more than others (e.g., climate change, contaminants, hypoxia, acidification, fish propagation, disease, and invasive species). Survival rates during the early marine life-stage have been particularly difficult to measure. A second uncertainty concerns how focal species and population diversity would respond to alternative restoration actions in the estuary versus in mainstem and tributary locations. The scale of data collection throughout the Basin is presently insufficient to estimate relative benefits of restoration by life stage and habitat. A third uncertainty concerns the current capacity of estuarine habitat to support focal species, its adequacy to achieve Program goals, and ways to increase that capacity. At present, it is generally assumed that habitat restoration efforts in the Columbia River estuary are increasing carrying capacity for salmonids, but additional research is needed to test this assumption and to quantify any increase in capacity.

Theme 7. Contaminants: Fish, wildlife, and human populations in the Basin and elsewhere in the United States are exposed to an ever-growing variety of pollutants as a result of increasing urbanization, industrialization, and agricultural development. The two uncertainties identified in the 2006 Research Plan are repeated here. The first concerns the proliferation of contaminants and the need to measure and map the spatial and temporal patterns of their use, transfer, accumulation and persistence. For example, a new interactive mapping tool developed by the National Water-Quality Assessment (NAWQA) Program shows predicted concentrations for 108 pesticides in streams and rivers across the United States and identifies which streams are most likely to exceed water-quality guidelines for human health or aquatic life. The second uncertainty concerns how contaminants affect fish production and survival. Aquatic communities in the estuary and coastal ocean are considered especially vulnerable to the accumulation of contaminants because of their spatial positions in the watershed. Studies of contaminants in invertebrate species, many of which are the first components of the food web to accumulate contaminants, are extremely rare in the Basin. Both uncertainties demand greater attention within the Program given the potential for contaminants to negate restoration efforts. However, addressing them will require a high level of integration and collaboration with state, tribal, and federal agencies.

Theme 8. Climate change: The three climate change uncertainties listed in the 2006 Research Plan are still relevant, but were restated as two uncertainties. The first uncertainty focuses on how long-term climate trends will affect fish and wildlife. Progress has been moderate for predicting changes in temperature and flow, but low for predicting changes in ecosystems. Predictions of increased temperatures and reduced snow packs and summer stream flows suggest that fish kills, such as observed in 2015, are likely to increase in frequency, extent, and severity. The second uncertainty concerns actions that could ameliorate the undesirable impacts of climate change. Special attention is needed to secure thermal refuges and sufficient high quality water under predicted landscape-scale changes in hydrology. Other water security issues that could affect the success of the Program include tradeoffs between water availability and energy production; and governance issues among countries, states, tribes, and other stakeholders. Two Program projects have directly addressed climate change, but more collaboration is needed with universities, other researchers, and policy makers. Future research will be a continuing process of fine-tuning climate models to understand and manage the impacts of climate change on hydrology, habitat phenology, and biota.

Theme 9. Non-native species: The 2006 Research Plan identified three uncertainties to guide ecological studies of threats posed by non-native species, and management actions to improve outcomes. Little progress has been made, and non-native species continue to arrive and spread to many parts of the Basin. Current Program projects are more focused on the impacts of piscivorous native species (e.g., northern pikeminnow, birds, and pinnipeds) than the impacts of non-native species. However, non-natives such as smallmouth and largemouth bass, walleye, northern pike, and lake trout have become more widely established as predators on salmonid juveniles, especially in reservoirs. Accordingly, the 2006 uncertainties still apply, but they were consolidated and restated as two revised uncertainties.

The first uncertainty concerns the extent to which non-native species now jeopardize the viability of native fish and wildlife. Non-native species change biotic interactions, create novel ecosystems, and have the potential to undermine otherwise successful habitat restoration efforts. Effects of non-natives on native fauna are seldom well understood, often involve complex interactions with other species and habitat types, are difficult to predict accurately, and may be recognized only after the native species are in steep and sometimes irreversible decline. Most non-native species are not fishes, and include invasive molluscs, lower trophic level taxa, aquatic vegetation, and pathogenic organisms that are unrecognized or unstudied by current projects. Studies to predict how non-natives will fare relative to native species under climate changes are lacking and will undoubtedly prove difficult to design and implement.

The second uncertainty concerns management actions that could limit the abundance and spread of non-native species, and mitigate their impacts. Once non-native species are established, efforts to remove them are typically unsuccessful. Management and policy decisions must consider both ecological issues and sometimes conflicting preferences of stakeholders and the public. Efforts to re-establish salmonids into blocked areas will require a greater understanding of the fish communities present in those areas, as non-native species are now often major components of those communities and habitats.

Theme 10. Predation: Predation was not specifically listed as an uncertainty in the 2006 Research Plan. However, new or expanded proposals to cull predators of salmon in the Columbia River estuary (e.g., double-crested cormorants and sea lions) have renewed controversy about the merits of such management approaches. The role of predators in maintaining community structure is often poorly appreciated, and controlling predator populations to reduce predation on threatened or endangered species may not be feasible. Accordingly, the ISAB and ISRP identified two new uncertainties related to predation.

The first uncertainty concerns the extent to which predators now jeopardize the viability of native fish and wildlife populations. Predicting the impact of predation on prey populations is complicated, especially if other factors are expected to change beyond historical norms. Predation on adult salmonids during upstream migration (e.g., by pinnipeds, especially sea lions) is of particular concern because it may reduce the potential spawning population more than an equivalent rate of predation at earlier life stages. Losses to predators early in life might be mitigated by compensatory mortality during later life stages, especially if predators selectively remove the least fit individuals.

The second uncertainty concerns the effectiveness of management actions to ameliorate undesirable impacts of predation. Past experience indicates that predator control is best used to solve a local and temporary problem and is generally not practical over a wide geographic area for biological and economic reasons. Removal of predators can also have counter-intuitive and unintended consequences for both the target populations and other predator and prey species. Thus, predator management requires a long-term strategy with careful treatment-control comparisons and monitoring.

Theme 11. Fish propagation: Hatcheries are widespread in the Basin, and consequently, it is critical to understand their effects on natural populations, both positive and negative. Despite significant progress by recent projects, the uncertainties related to fish propagation identified in the 2006 Research Plan are still relevant. To reduce overlap and redundancy, the seven uncertainties listed in the Research Plan have been recast into five uncertainties.

The first uncertainty concerns the cumulative effects of basinwide hatchery production on natural populations given the various ways that hatchery fish can interact, both directly and indirectly, with natural origin fish. For example, it is unclear whether or not the cumulative impact of hatchery releases on density-dependent responses in natural populations is adequately considered in planning supplementation efforts.

The second uncertainty concerns the extent to which production by natural populations can be improved by supplementation. Evaluation of this uncertainty requires pre- and post-project reference streams, infrastructure to sample juveniles and adults, and genetic analyses to ascertain the pedigree of natural origin fish. In several subbasins, hatcheries are also being used to reintroduce salmonids into areas where the original populations were extirpated. Monitoring and evaluation of supplemented and reintroduced populations are needed to track abundance, local adaptation, and straying rates, as well as impacts on other species.

The third and fourth uncertainties relate to the potential roles and impacts of artificial propagation and translocation to restore the abundance and distribution of Pacific lamprey and white sturgeon, respectively.

The last uncertainty is about the genetic or epigenetic changes that occur in cultured populations, and the impacts of such changes on the fitness of natural populations. A component of this uncertainty is the efficacy of management guidelines that regulate the percentage of hatchery origin spawners (pHOS) in nature, and the proportion of natural origin fish used as broodstock (pNOB). Although these management guidelines are well supported by scientific theory, additional empirical assessments are needed to verify their adequacy for protecting the fitness of natural populations.

Theme 12. Harvest: Despite some progress, three uncertainties related to harvest proposed in the 2006 Research Plan were only slightly modified. The first uncertainty concerns how to define biological escapement goals that balance the tradeoffs among fishery harvests, potential ecosystem benefits of increased spawning abundances, and pHOS guidelines to protect fitness in (i.e. genetic adaptations to) the natural environment. Some biological escapement goals already exist within the Basin, but more are needed, as acknowledged in the 2014 Program.

The other two uncertainties emphasize the need to develop: (1) new strategies to improve harvest opportunities within the Basin that minimize negative impacts on natural populations of concern (e.g., by selectively harvesting hatchery origin fish); and (2) better ways to manage coastal mixed-stock fisheries to protect natural populations of concern. Managing and evaluating harvest impacts on natural-origin populations requires reliable information on the stock composition of fish in mixed-stock fisheries both within and outside the Basin. Newly emerging tools could improve the accuracy and the cost effectiveness of stock identification.

Theme 13. Population structure and diversity: Human activities have reduced the range of life history strategies and genetic diversity in many native fish populations. Loss of genetic diversity is expected to compromise the long-term productivity and adaptability of individual populations, as well as the aggregate production and resilience of collections of populations. Understanding population structure (i.e., how diversity is distributed among populations of a species) is also essential for evaluating the viability of a species.

Only limited progress was achieved on the four uncertainties listed in the 2006 Research Plan. Many additional questions broadly related to this theme were also listed in the uncertainties database, reflecting the diversity of life histories and habitats for focal species in the Basin, and the inherent focus of population studies on individual species. Consequently, five more uncertainties (nine in total) related to this theme were identified. Three of the uncertainties reflect a lack of knowledge about (1) factors affecting demographic status of fish and wildlife populations in the Basin, (2) the existing range of biological diversity among geographic areas in the Basin, and (3) alternative life history strategies in fishes and how they affect growth and survival in different habitats. Co-occurring life-history types (e.g., resident versus anadromous rainbow trout, ocean versus reservoir type fall Chinook) that differ in their habitat requirements or productivity can pose special challenges for habitat restoration or harvest management.

Two other uncertainties reflect a lack of knowledge about (1) the dominant processes influencing the distribution and interconnection of populations and (2) the long-term consequences of losing connectivity and populations. The sixth uncertainty concerns the effectiveness of genetic assessment tools for determining trends in population status and population diversity.

The last group of uncertainties involves management approaches for protecting the population structure and viability of species groups of particular interest. The seventh uncertainty is how the abundance and diversity of salmonid populations in the Columbia River can be increased and sustained over the long term given the multitude of biological, physical, and human constraints. The eighth and ninth uncertainties are concerned with threats to the abundance, distribution, and diversity of Pacific lamprey and white sturgeon, respectively. It will be important to identify and protect diversity in Pacific lamprey in tandem with artificial propagation efforts. Habitat connectivity is likely a critical issue for the long-term viability of white sturgeon.

Theme 14. Monitoring and evaluation: Monitoring and evaluation of projects has improved substantially since the 2006 Research Plan because of technological progress (e.g., geographic information systems and remote sensing tools, better tagging methods including genetic methods for stock identification and parentage-based tagging, and superior analytical methods); standardization of protocols (e.g., Columbia River Habitat Monitoring Program); and a stronger focus on the need for monitoring and evaluation during project reviews at various levels. Sound statistical planning for monitoring is essential to ensure proper evaluation of project effectiveness and to identify how monitoring data can be integrated and synthesized across projects to maximize the scope for inference.

Accordingly, four new uncertainties related to monitoring and evaluation were identified. These uncertainties focus on the need to improve (1) the precision and accuracy of methods used for estimating fish survival, (2) methods for "fish-in and fish-out monitoring" to evaluate density dependence and the benefits of habitat restoration, (3) approaches to measuring the cumulative effects of habitat restoration on fish populations at a large spatial scale, and (4) evaluation of impacts of habitat restoration on wildlife, recognizing that changes to habitat that benefit fish might not benefit other species.

Dissemination of Information

After reviewing annual reports from 187 Program projects with research, monitoring, and evaluation components, the ISAB and ISRP came to more fully appreciate the range of topics currently being addressed in the Basin. Excellent research and monitoring are occurring, innovative approaches are being tried, and research teams are using a variety of methods to address problems. However, we believe benefits to the Program could be increased by greater communication among the project proponents and other practitioners. For example, annual reports should routinely include syntheses of results from previous years, including lessons learned about approaches and methods. Better dissemination of these findings will improve the collective rate of learning about successful approaches and methods.

Substantial progress could be realized by better communicating the focus, results, and findings of projects within the Program. To improve accessibility, this information needs to be summarized carefully and placed consistently into a single location that can be searched easily. To this end, abstracts produced by project teams should be compiled as a comprehensive annual report for the Program that could, for example, be linked to the Council's web page.

Stronger linkages between project reporting and critical uncertainties in the Research Plan are also needed to track annual progress in resolving uncertainties. Without being burdensome, the annual reporting process should require project teams to explicitly identify which uncertainties are being addressed, and how. These statements could be incorporated into the annual report for the Program (as proposed above) or into a separate, searchable document.

Moving Forward

The following recommendations are provided to help revise the Research Plan and improve research within the Program during the next five years.

- Improve communication on research issues and results among project proponents, the public, governmental entities, the Tribes, and others involved with the Basin's water, land, and fish and wildlife resources. Communication leads to partnerships, pooling of resources, spreading of innovations, public support, and solutions that would be difficult for one or a few organizations to achieve alone.
- Foster efforts to synthesize information generated by independent studies by improving the rigor, consistency and availability of annual reports, convening workshops or symposia, and funding special projects as needed to compile, analyze, and review progress in addressing uncertainties.
- Recognize that research on the expected impacts of climate change and human development in the Basin should be taken into account when setting future Program objectives.
- Support research to identify thermal refuges and ways to secure the availability and quality of water essential to achieving Program objectives.
- Recognize that toxic contaminants are pervasive in the Basin and support research to determine threats to fish, wildlife, and people because of their persistence and bioaccumulation in food webs.
- Support research to guide the management of non-native species. As conditions change, environments may increasingly favor non-native species, some of which are valued and can be managed.
- Continue supporting research on artificial propagation that will help to measure the benefits and risks to natural populations. Encourage research to help develop biological escapement

goals for the Basin's salmonid populations and refine approaches for harvesting surplus hatchery fish.

- Expand research to identify and track changes in population structure and genetic diversity of focal species. Loss of genetic diversity may compromise the long-term production and resilience of fish and wildlife in the Basin.
- Continue to support and demand rigorous monitoring and evaluation programs that have well established objectives and potential for basinwide synthesis. Such evaluation is needed to understand the benefits and risks of Program actions and to manage adaptively.
- Recognize that evaluating the effectiveness of conservation actions is complicated by natural variability and statistical sampling error. Many years of careful monitoring are typically required to confirm small but meaningful changes in ecological outcomes from habitat restoration or supplementation projects.
- Support research on ecological interactions in mainstem, lower Columbia River, estuary, ocean plume, and ocean habitats. Understanding the factors in each habitat that limit population growth will improve management of all four H's (habitat, harvest, hatcheries and hydrosystem).

Preface: Review Charge, Approach, and Products

The 2014 Fish and Wildlife Program[2] calls for the Northwest Power and Conservation Council to review ongoing research and revise the Program's Research Plan (Council Document 2006-3), which includes a list of "critical uncertainties" that identify important gaps in knowledge of resources and functional relationships that determine fish and wildlife productivity in the Columbia River ecosystem.[3] The Council's process includes the ISAB and ISRP's role to "assist with updating the critical uncertainties, taking into account evolving topics and reporting on the results of past research" (FWP, p. 104).

In a February 23, 2015 letter,[4] the Council asked the ISAB and ISRP for a report that includes:

- A revised set of critical uncertainties
- A detailed list of research themes or categories that fully encompasses past, current, and possible future research
- Scientific input on identifying priorities among the critical uncertainties
- A determination of whether ongoing research is making progress in answering critical uncertainties listed in the current research plan (2006 Research Plan)

The ISAB and ISRP addressed this request through two ambitious review efforts, and the findings are presented here in two parts. Part 1 is forward looking and addresses the Council's first three bulleted items. It provides a revised set of critical uncertainties (i.e., questions); organizes the uncertainties under a detailed, hierarchical outline of themes and sub-themes; describes progress on addressing the critical uncertainty; and provides the ISAB and ISRP's rationales for prioritizing uncertainties in the Council's uncertainties database. Uncertainties are identified as high priority (i.e., critical) if addressing them would substantially improve decision-making and management actions to protect, mitigate, and enhance Columbia River Basin (Basin) fish and wildlife. In completing Part 1, we refined the Council's draft uncertainties database, which contains uncertainties that Council staff identified from over 130 regional reports and plans including uncertainties submitted during the 2014 Program amendment process.

Part 2 contains a retrospective analysis that answers the Council's fourth question: "Is ongoing research making progress in answering critical uncertainties in the current [2006] research plan?" Specifically, ISAB and ISRP review team members evaluated the most recent annual progress reports for 187 ongoing 2015 Fish and Wildlife Program projects that contained a research, monitoring, or evaluation work element. The reviewers determined the extent to which the projects directly addressed or could potentially help address the 2006 Research Plan's 44 critical uncertainties. We considered other sources

[2] Referred to as "Program" or when in a citation "FWP."

[3] The Council's Program defines critical uncertainties as "questions concerning the validity of key assumptions implied or stated in the program." The Scientific Review Group (precursor to ISAB and ISRP; SRG 93-3) defined critical uncertainties as "important gaps in our knowledge of the resources and functional relationships that determine fish and wildlife productivity in the Columbia River ecosystem."

[4] The ISAB Administrative Oversight Panel and Ex Officios from the Council, NOAA Fisheries, and the Columbia River Inter-Tribal Fish Commission provided input on the request letter and approved the ISAB assignment.

of outside work and literature relevant to the uncertainties, but because of the review scope and time constraints, that effort was opportunistic. Thus, our reviews are based on reviewers' knowledge, rather than a comprehensive literature review on the state of the science for each question. We summarize our findings for the 44 uncertainties in the main body of Part 2, titled *Summary of Progress toward Addressing 2006 Research Plan Critical Uncertainties*.

Appendix D to Part 2 include our evaluations of the annual reports for projects funded by the Program. Our evaluations identify the types of information reported by the projects (e.g., biological or physical habitat data) and the 2006 uncertainties that were directly or indirectly addressed. We also commented on each project's methods, the relevance of each project's results to the Program and the 2006 Research Plan, the applicability of the results at the project or program scale, and the time likely required for each project to generate useful conclusions. These topics reflect the Program's criteria for prioritizing critical uncertainties (FWP, p. 104). Part 2 addresses the ISRP's review charge to evaluate the results of prior year expenditures as called for in the 2014 Fish and Wildlife Program and the 1996 Amendment to the Power Act, in the past referred to as ISRP retrospective reviews. The ISRP recognized that reviewing project results in the context of revising the 2006 Research Plan adds value to the retrospective review.

Under Parts 1 and 2, the ISAB and ISRP provide Programmatic Comments where relevant. They often apply across projects, uncertainties, and research themes. These comments covered process issues such as the quality of annual reports, infrastructure issues such as how best to design research efforts to address basinwide questions, and scientific issues such as emerging uncertainties involving water quality and water security.

This ISAB and ISRP review and identification of critical uncertainties is one step in the Council's process to update the Program's research plan. Subsequent steps will ensure meaningful opportunity for public input. ***We emphasize that our evaluation is largely based on our review of annual reports of current Fish and Wildlife Program projects and the cumulative knowledge and expertise of our members rather than a quantitative analysis of empirical data or extensive review of the current scientific literature pertaining to each uncertainty. To increase consistency in our evaluations, we developed guidance criteria for identifying and prioritizing uncertainties. Nevertheless, we want to acknowledge and emphasize the qualitative nature of the prioritization process.***

Additionally, we did not explicitly consider economic or policy information, although cost is included in the Program's criteria and is a key consideration for the Council's prioritization of activities to meet its mitigation obligations (see Appendix A). We emphasize that additional contributions from fish and wildlife managers, project proponents, researchers, and others are needed to inform the Council's research plan development process. We welcome any follow-up role that the Council may identify for the ISAB and ISRP, including a potential review of the Council's draft revised research plan.

Part 1. A Revised Set of Critical Uncertainties

Review Process

Part 1 provides a revised set of critical uncertainties, which we winnowed down from the original extensive list. The remaining uncertainties were organized hierarchically by themes and sub-themes.

To complete Part 1, the ISAB and ISRP followed a multi-step process. First, we examined the Council's draft uncertainties database, which contains a compilation of uncertainties drawn from over 130 regional reports and plans including uncertainties submitted during the 2014 Program amendment process. Second, we developed a detailed list of research themes to help classify and organize the compiled uncertainties. Third, we developed guidelines to judge the progress of ongoing research and level of criticality of each issue and then applied these guidelines to identify critical uncertainties. Finally, we re-examined the list of critical uncertainties to identify those most critical (i.e., Priority) to the Program. It is important to note that many of the critical uncertainties may be very difficult to address, especially in single objective, short-term projects. As a result, many critical uncertainties have yet to be comprehensively studied.

Step 1. Working with the Council's draft uncertainties database

In its review request letter, the Council encouraged the ISAB and ISRP to consider a wide range of uncertainties including those submitted during the program amendment process, identified in the Program, and described in other Basin plans such as Biological Opinions, recovery plans, and tribal programs. Before our review, Council staff had reviewed these and other sources (including ISAB and ISRP reports), identified uncertainties or statements that could be research topics, and compiled a list of about 1400 uncertainties in a draft uncertainties database. The source of each uncertainty was recorded in the database along with other contextual information. When we began this review in April 2015, Council staff had begun to refine the database by merging redundant questions and categorizing the uncertainties. Although the task was daunting, we recognized the potential value of the Council staff's effort to develop an uncertainties database, which could facilitate tracking progress toward addressing the uncertainties. Accordingly, we helped the Council staff to refine the database as a tool for revising the list of critical uncertainties.

Step 2. Developing a more detailed list of research themes or categories that fully encompasses past, current, and possible future research

We addressed this review request by first comparing the high level themes in the 2006 Research Plan, the 2014 Fish and Wildlife Program, and the Taurus project database, recognizing that the themes we would select for uncertainties should be consistent with the Program's strategies and emerging priorities. Based on that comparison, we reconciled differences among the documents and identified the following 14 primary themes:

- public engagement
- human development
- tributary habitat
- hydrosystem flow and passage operations
- mainstem habitat
- estuary, plume, and ocean
- contaminants
- climate change
- non-native species
- predation
- fish propagation
- harvest
- population structure and diversity
- monitoring and evaluation methods

We chose general themes that apply to more than one species because the database allows users to select uncertainties relevant to a particular species group such as Pacific lamprey or white sturgeon. Although each uncertainty is categorized under a single theme that seemed most appropriate, most uncertainties represent an interconnection of topics and require an ecosystem approach to fish and wildlife research and management. An ecosystem approach is consistent with ISAB's past recommendations for revised scientific principles of the Program that emphasize ecosystem resilience and adaptability (ISAB 2013-1).

For each of the 14 primary themes, an ISAB and ISRP team with appropriate expertise was formed to (1) evaluate the sets of uncertainties, and (2) develop a more detailed outline of subthemes or categories. To do this, teams reviewed the 2006 Research Plan questions, identified the range of subthemes covered by the sets of uncertainties in the database, and developed outlines to reflect a logical flow of inquiry under each primary theme. In general, uncertainties were organized under three subthemes: (1) assessment, (2) impact, and (3) management to reflect the Council's desire for more detailed categorization than in the 2006 Research Plan. Subthemes were identified because broad themes include many components, some of which are intractable or may require a sequence of research actions to address them. A refined categorization can help reveal research progress and gaps, for example, by indicating that uncertainties under a particular subtheme have been addressed whereas uncertainties under another subtheme have not been addressed.

Step 3. Providing scientific input on identifying priorities among the critical uncertainties (priority research questions)

Information generated by efforts to resolve critical uncertainties can be used to improve the effectiveness, including the cost effectiveness, of fish and wildlife restoration and management. Thus, the Council asked that the ISAB and ISRP prioritize the uncertainties by considering their implications for fish population viability and Program mitigation obligations. The Council suggested that the 2 x 2 risk uncertainty matrix[5] approach described in the 2014 Program be used, as applicable, in the prioritization process. This 2 x 2 approach was modified by the ISAB and ISRP to include three considerations: (a) the potential benefits toward achieving the Program goals if an uncertainty were to be completely or partially resolved, (b) the value of new information obtained from resolving an uncertainty, and (c) the

[5] Further details on the Council's 2 x 2 risk uncertainty matrix can be found in the Council's 2014 Fish and Wildlife Program (pages 102-104).

cost of producing new information. A full explanation and conceptual framework for this new procedure can be found in Appendix A titled *Challenges for Prioritizing Uncertainties to Guide Management Decisions.* The ISAB and ISRP effort to identify and prioritize critical uncertainties focused on the first two considerations (potential benefits and the value of information). The financial costs associated with resolving an uncertainty are difficult to estimate until research plans are fully developed. Therefore, although important, costs were not explicitly considered in this exercise

During the prioritization process, we judged whether resolving an uncertainty would allow managers to perform actions that would provide benefits to the Program using the following factors:

1. Importance of benefits (e.g., legal imperative such as ESA or Treaty rights)
2. Certainty of the benefits (probability of success)
3. Spatial scale of benefits
4. Duration of benefits
5. Adaptive management (learning) benefits
6. Feasibility of obtaining benefits

Second, we also appraised the probable value of information obtained by the research efforts used to resolve an uncertainty by considering the issues listed below:

7. Feasibility of performing research on an uncertainty
8. Spatial applicability of the information
9. Temporal applicability of the information
10. Relevance to more than one species
11. Added value or complement to other information or decision-support tools, e.g. predictive models

The process of examining and placing uncertainties in each primary theme into a hierarchical outline of subthemes allowed Council staff and ISAB and ISRP members to identify and merge redundant uncertainties. The teams then estimated the amount of progress that had been made in addressing the slightly more than 700 remaining uncertainties. Each team also assessed the importance (criticality) of each uncertainty. Prior to making these appraisals, general guidance on how progress and criticality should be assessed were developed (see Appendices B and C). Three criticality ratings were possible: low, medium, and high. Over 200 uncertainties that would improve decision-making and management actions to protect, mitigate, and enhance Basin fish and wildlife were given "high" criticality ratings. We re-examined the uncertainties given a high rating and produced a set of "priority" critical uncertainties within each primary theme that the Council could consider when developing its new Research Plan. These 50 "priority" critical uncertainties, along with rationales describing why they were judged to be priority questions are presented below (see List of Priority Critical Uncertainties by Theme).

Establishing Infrastructure Needed to Address Uncertainties

Many of the uncertainties that are present in the Council's database are too broad for one or even a small set of research projects to address. Typically, research projects in the Basin are focused at or below the subbasin level, last for several years, and are conducted by scientists with expertise in one or two disciplines. What is needed, however, are studies lasting for a decade or more that involve multiple subbasins and are conducted by an integrated team of professionals representing a diverse array of disciplines, including fisheries, ecology, hydrology, modeling, and the social sciences. Creating and supporting such teams will provide opportunities to make substantial progress in resolving many of the uncertainties described below.

The ISAB and ISRP recommend establishing the necessary infrastructure to adequately address critical uncertainties (CUs) at the level of spatial, temporal, and analytical complexity commensurate with the uncertainty. This recommendation is in keeping with the 2006 Research Plan, which suggests a "Regional Research Partnership: A Forum for Collaboration" and describes the potential of the Plan to:

- *Foster agreement on a manageable number of well-chosen priorities*
- *State the priorities in ways that promote effective research solutions*
- *Provide a means for resolving disagreements on priorities*
- *Take advantage of unforeseen research opportunities that arise from advancements in technology and scientific knowledge or are simply facilitated by immediate environmental or social opportunities*
- *Foster collaborative research with other entities* (2006 Research Plan, page 42)

Program projects have already acquired massive amounts of information (data) that require sophisticated analyses and synthesis in order to be most useful for Program effectiveness and efficiency. These analyses cannot be successfully performed by existing projects for a variety of reasons, including the broad scope and high level of complexity of the CUs, which are beyond the capability of individual projects to address. Critical to the Program's success are the "information channels" that are created to organize the flow, interpretation, processing, storage and maintenance of accumulated knowledge (*see* Appendix A). The cumulative value and usefulness of information can decay quickly without an institutional scaffold to sustain it. As indicated above, the 2006 Research Plan emphasized the need for a basinwide partnership; however, that recommendation appears not to have been implemented.

Addressing this need for an improved and more effective institutional infrastructure is complex but could be accomplished in at least three ways. One approach might be to establish an Institute with an exclusive focus on the Basin. The Institute could be based in one location, or it could be an identifiable association of scientists and personnel from multiple agencies and organizations with a common goal of solving fish and wildlife problems in the Basin. A second, somewhat less comprehensive approach might be to foster research design and implementation teams with specific agreements for coordination and collaboration. Examples of research teams include the Ad Hoc Supplementation Work Group, the

Integrated Status and Effectiveness Monitoring Program (ISEMP), the Columbia Habitat Monitoring Program (CHaMP), and the Comparative Survival Study (CSS); the CSS enables the states and tribes to collaboratively examine salmonid passage and survival. Such an Institute or research team would require guaranteed funding for a decade or more (funding commensurate with the severity and scope of the CUs that are being addressed). A third approach might be to formulate specific Requests for Proposals to address several of the top priority CUs. Successful proposals could include several entities and be given adequate time and funding to resolve the issues. While there may be other approaches to establish multi-entity partnerships, the key point is that the Program's effectiveness could be greatly improved by a regional approach to RME, better coordinated use of existing RME infrastructure and data, and implementation of a broad based (landscape) perspective—as we previously described (ISAB 2011-4).

List of Critical Uncertainties by Theme

The themes below are sequenced in an order similar to the 2014 Program's organization of strategies. The order does not reflect a prioritization of themes. We placed the Public Engagement theme first because it provides context for all the other themes. The Public Engagement theme includes more citations and text than the other themes because it was not addressed in the 2006 Research Plan or in Part 2. Example sub-uncertainties are listed under many of the priority uncertainties and were limited to four or less per uncertainty. These examples are intended to show how a broad critical uncertainty might be broken into more tractable sub-uncertainties, which could be addressed by research projects or subdivided further as needed so they could be addressed. The inclusion or absence of example sub-uncertainties under priority uncertainties does not imply relative priority of the uncertainties.

Public engagement

The success of the Program depends on public engagement. Public engagement involves the exchange of information between program sponsors and participants—including the general public. Public engagement can be divided into three types: (1) public communication, (2) public consultation, and (3) public participation (Rowe and Frewer 2005). The Program includes a wide range of activities for which public participation and consultation are essential.

Public engagement, for example, is important to successful restoration at the landscape scale. The ISAB report on *Using a Comprehensive Landscape Approach for More Effective Conservation and Restoration* (ISAB 2011-4) stated that four elements need to be addressed simultaneously for the Program to be successful. They are (1) a program with a scientific foundation based on principles from landscape ecology and on the concept of resilience, (2) broad public support for long-term stewardship, (3) a governance that allows for collaboration and integration, and (4) a capacity for learning and adaptation. Elements 2 and 3 directly address aspects of public engagement and were incorporated in the 2014 Program. To achieve these four program elements specific actions are required, including: (1) establishing species and habitat diversity, (2) strengthening linkages between science and management,

(3) increasing public engagement, (4) working across traditional ecological and social boundaries, and (5) learning from experience.

None of these elements are explicitly identified as a critical uncertainty in the 2006 Research Plan, with the possible exception of the fourth element which is only partially addressed through adaptive management. The Council, responding to recommendations from the ISAB (ISAB 2013-1), included public engagement as the sixth guiding scientific principle in the amended 2014 Program. In addition, the 2014 Program includes a strategy on public engagement, and the Program cites and lists the ISAB's recommendations (ISAB 2013-1) as principles for public outreach and involvement. The Program also urges the Council to "*monitor the success of its outreach and involvement efforts*" (FWP, p. 99). In order to support the Program's commitment to Public Engagement, the ISAB and ISRP identified five uncertainties believed to be critical to program effectiveness and success.

Specific actions are required to adjust restoration goals so that they reflect the elements of the landscape approach articulated above. These include addressing species and habitat diversity, strengthening linkages between science and management, increasing public engagement, working across traditional ecological and social boundaries, and learning from experience.

The ISAB and ISRP included public engagement as a theme related to critical uncertainties because we recognized that progress towards addressing critical uncertainties, whether via monitoring, evaluation, or implementation, ultimately depends on public engagement. While critical uncertainties are associated with each of the three types of public engagement described above, the following five critical uncertainties are closely tied to the program elements judged to be important for setting priorities for the next phase of the Program.

1. How well does the Fish and Wildlife Program communicate with and engage the public (and its diverse social groups) associated directly or indirectly with the landscape?

Tracking and analyses of the engagement and diversity of groups involved in Program efforts are vital for long-term success. This requires analyses of engagement outcomes (their effectiveness and cost-effectiveness), communicating results of Program projects to the public and to local decision makers, and evaluating the impact of these activities on management and public support for restoration actions. New knowledge that could improve management will have no impact if it is not disseminated. But while effective dissemination may be a necessary condition, it may not be sufficient to ensure expected outcomes due to a range of factors including community perceptions, beliefs, and mental models that lead to differing reactions to scientific information. These factors often influence decisions of local governance groups, private citizens, non-governmental organizations (NGOs), restoration practitioners, and other participants in regional conservation and restoration efforts.

2. How well does the Fish and Wildlife Program strategy incorporate the human-related aspects of landscape ecology and resilience?

Projections of future trajectories of fish and wildlife populations are not likely to be robust unless they incorporate changing patterns of land use and land cover. Public engagement of local, state, and federal land use planners and natural resource economists could improve projections of changes in the landscape (Hulse et al. 2004). Models of socioeconomic change could also help to predict future landscape conditions and their effects on restoration efforts or the resilience of threatened salmon populations and other focal species.

3. How well does the Fish and Wildlife Program strategy develop organizations that support collaboration, integration, and effective governance and leadership?

The study of public engagement in environmental issues can provide guidance in understanding how scientists, working with others, can contribute to effective solutions. Promotion of more collaborative and participatory decision-making at multiple governance levels has gained attention in recent years. Adherents of this approach point to the need for more collaboration among NGOs, governments, and businesses (Newig and Fritsch 2008)*. The actual benefits of public engagement are difficult to evaluate, rigorous evaluation is both complicated and rare (Rowe 2005), and the evidence is mixed (Newig and Fritsch 2008). One factor important to public engagement is community homogeneity—research has shown that public engagement is lower in more-heterogeneous communities (Costa and Kahn 2003). Coordination and cooperation are costly; they incur transactions costs, i.e., expending time and effort to establish channels of communication and to decide which entities, among a multitude of potential cooperators, represent sources of information and communication that are sufficiently valuable to warrant investments and continued expenditures (see Arrow 1974). These transaction costs can be high, and the benefits of cooperation must be sufficiently large relative to those costs for each participating entity to justify their continued involvement, otherwise collective engagement is unlikely to be sustainable.*

Although in some cases conservation and restoration actions appear to be working at odds with each other, resolving the conflicts are not always straightforward. Adaptive problems, such as river conservation and restoration, are socially and ecologically complex, the solutions to these problems are not known, and even if they were, no single entity has the resources or authority to bring about necessary changes (Naiman 2013). Reaching effective solutions generally requires innovation, sharing new information, and learning by members of the public involved in the problems (Ostrom 1990, Lee 1994). Success can depend on the willingness of the public to change their behaviors in ways that are viewed as costly or simply contrary to habit, belief, or tradition (Ostrom 2014).

International examples suggest that large-scale common pool resources (e.g., entire watersheds) can be successfully managed (Ostrom 1990). Such successes typically require coordination among governments with multiple overlapping jurisdictions and among multiple NGOs (e.g., Morton Bay, Australia; see Sarker et al. 2008 and Bunn et al. 2010). The challenges as well as successful examples have been well documented (Bromley and Cernea 1989, Ostrom 1990, 2009).

The challenges, which are likely to be site specific, amount to discovering the best way to engage and coordinate with government entities at various jurisdictional scales, and with NGOs, to promote public communication, consultation, and participation to further the goals of the Program. An initial step would be to support organizations that show promise for assisting with coordination, integration, and leadership toward achieving Program objectives.

4. How well does the Fish and Wildlife Program strategy promote adaptive capacity based on active learning through assessment, monitoring, innovation, experimentation, and modeling?

Annual variability and long-term change are inherent properties of landscapes, ecosystems, and fish and wildlife populations and are also difficult to anticipate. Attempts to manage for a specific benefit may disrupt adaptive capacity and resilience of riparian and aquatic ecosystems by simplifying the diversity of habitats, altering connectivity, and disrupting mechanisms for feedback. Damage to the adaptive capacity of the ecosystem could also significantly harm human communities that depend on salmon and other species.

Many future ecosystems will have no natural or historical precedent (ISAB 2011-1) due to factors such as non-native species (ISAB 2008-4), climate change (ISAB 2007-2), and extensive land cover conversion (ISAB 2003-2, ISAB 2011-4). Adaptive management is a cornerstone of the Program because it provides a robust mechanism to learn about changing landscapes, ecosystems, and populations and to revise our actions appropriately. Another cornerstone is the concept of resilience, which argues that diversity, modularity, and feedback lead to retention of adaptive capacity. Resilience includes anticipation that change is to be expected and there is a need for alternatives and flexibility to new situations and challenges. For this reason, many organizations are working to integrate biophysical and socioeconomic science with environmental and resource management. This integration is intended to improve management decisions and also strengthen adaptive capacity and ultimately the resilience of human-natural systems faced with change. More specifically, monitoring and modeling are already major elements of the Program, but there could be greater attention to active learning in broader social and economic settings with more interactive tools.

5. How well does the Fish and Wildlife Program incorporate a clear process to generate new information and revise objectives, strategies, and actions in response to that information?

Adaptive management is a process for deciding better approaches when science points toward an improved policy, when knowledge is incomplete, or when there is considerable uncertainty about future conditions. For example, one option for ecosystem management may require control and homogenization of ecosystems, but such an approach can reduce the biological diversity needed for adaptive capacity. Adaptive management allows scientific knowledge from monitoring, modeling, and assessing the linkages and feedbacks of coupled human-natural systems, to be used to make predictions, set new goals, and identify mechanisms to achieve those goals. Adaptive management also benefits from innovation and comparison among groups engaged in similar activities. One of the Program's primary goals is to improve resilience and *adaptive capacity of fish and wildlife populations through an effective feedback of learning through experimentation, innovation, and sharing new knowledge. The uncertainty relates to how well the Program is incorporating adaptive management into program improvements. Evaluating the use of adaptive management requires assessment of 1) the institutional process for program management, 2) the designs of future objectives and strategies, and 3) the operational processes associated with regional decision making. (See Programmatic Comment 1)*

Programmatic Comment 1. Improved coordination with land management agencies

The 2014 Fish and Wildlife Program provides strong emphasis on the protection and restoration of ecosystem function at a landscape scale (see also ISAB 2011-4 and 2013-1). It provides direction for strong public engagement and emphasizes the use of collaboration and coordination in Program implementation, especially for the protection and restoration of tributary watersheds and riparian and aquatic habitats. Additionally, the 2014 Program states "*Ecosystem function can be improved in the Columbia and Snake river tributaries by, for example, repairing and restoring riparian habitat in spawning areas, restoring native vegetation, and changing land-management practices that can degrade water and habitat quality.*" The 2014 Program, however, does not directly address the critical role that management of federal and state lands in the Basin plays in making it possible to achieve many of the Program goals and objectives, particularly in a sustained fashion over the long term. These lands contain more than 50% of the remaining accessible anadromous habitat and comprise the headwaters of most major tributaries, and thus they significantly influence downstream water quality and aquatic habitat conditions for many tributary river systems.

There are more than 20 National Forests in the Basin and three Forest Service Regional offices, which have responsibility for managing the lands and the resources on these lands. A large portion of the best remaining habitat for salmon, especially spring Chinook, coho, and steelhead, as well as important strongholds for bull trout and west slope cutthroat trout, are found on National Forest System lands. There may be opportunities for the Council to coordinate in managing these lands.

Generally, each National Forest contains portions of several individual subbasins (normally 3-6). Land and resource management for these units is guided by individual Forest Plans. These Plans identify the general types, intensities, and locations of resource management activities and determine the level of protection and restoration for various resources and habitat types. This management is done through land allocations and development of standards and guidelines for the planning and implementation of resource management activities. Typically, each of these Plans provides management direction for the protection and restoration of watershed conditions, riparian and aquatic habitats and water quality. Many of the Plans also designate a network of specific watersheds, having excellent or restorable conditions, for special management emphasis for aquatic resources. These areas are strongholds or aquatic refuges that receive highest priority for the protection and restoration of fish habitat and water quality. Associated with the Forest Plans, are multi-federal agency, long term, effectiveness monitoring programs to assess trends in watershed condition (Aquatic and Riparian Effectiveness Monitoring Program [AREMP]) and aquatic habitat (Pacfish-Infish Biological Opinion [PIBO]). Coordination and communications in the development, revision, and implementation of these plans offers a range of opportunities to accomplish overlapping and often similar goals for riparian and aquatic habitat. Similar opportunities exist for lands managed by the Bureau of Land Management.

There is surprisingly good general alignment in approach and philosophy between the Forest Plans and the 2014 Program—both strive to protect and restore ecosystem function and establish a priority of conserving healthy habitat. Nevertheless, there appear to be major opportunities to improve Program effectiveness through active communication and coordination with the Forest Service and other federal agencies. Currently, there is no specific direction to promote active Council engagement in the development, review, and comments for these land and resource plans, some of which may have direct bearing on the Program's success. Ensuring active communication and coordination will provide major opportunities for cooperative and complementary approaches for sustainable protection and restoration of tributary habitat. As emphasized by the ISAB (2011-4), a landscape perspective is critical for effective habitat conservation and restoration. To achieve this will require more effective coordination and cooperation among all players.

Human development

1. How might the projected changes in society's use of land and other resources, as well as protection and restoration efforts under different future scenarios, affect environmental quality, habitats, and fish and wildlife populations? What changes in human population levels and their distribution, per capita income, and economic activity are expected over the next 20 years?

There is uncertainty about changes in the human system and in society's support for restoration efforts, including how changing preferences will affect collective actions. The human and natural systems of the Pacific Northwest are not static, and changes such as population growth, land development, and technological innovation will influence the effectiveness of restoration efforts. Most models of projected salmon and steelhead populations in the Basin do not incorporate future change in the human system. Fortunately, growth in population and associated changes in land use can be predicted, indicating areas where landscape and riverscape changes are most likely to occur (e.g., due to urban expansion). Other changes that will impact environmental quality, water scarcity, and resource depletion may be more uncertain. Effects of future changes in human systems on natural resources can be projected and evaluated with a range of model types representing coupled human-natural systems. This critical uncertainty combines two critical uncertainties from the 2006 Research Plan; see Part 2, Critical Uncertainties (CUs) #39 and 40, for the ISAB/ISRP discussion of progress made toward addressing this uncertainty.

Tributary Habitat[6]

1. How much can restoring habitats (e.g., for spawning, rearing, and refuges) in tributaries mitigate for degraded conditions throughout the rest of the Basin (e.g., mainstem habitat lost to dams, degraded estuary habitat, and unfavorable ocean conditions)?

This is the most critical question of the Tributary Habitat theme, and it must be addressed at the largest scale and throughout entire fish life cycles. The main issue is that the benefits of restoring tributary habitat interact with mainstem, estuary, and ocean habitat conditions, with fish passage through the hydrosystem, and with other stressors such as non-native species and toxic chemicals. These interactions are not well understood. By addressing this uncertainty managers will know whether restoring tributary habitat to mitigate for degraded habitat elsewhere is effective, and the use of available resources will be improved. This critical uncertainty was modified from the 2006 Research Plan; see Part 2, CU #13, for a discussion of progress made toward addressing this uncertainty.

Example sub-uncertainty:

1.1. What watershed and landscape-scale configurations and combinations of protected and restored habitats (aquatic, riparian and upland) are most effective at meeting the life cycle needs and sustaining populations of fish and wildlife in tributaries?

2. Can habitat restoration, removing barriers, and transporting fish above barriers sufficiently increase carrying capacity to recover native wild fish populations in the face of introduced hatchery fish and non-native invasive species that also compete for the same resources?

The goal of restoring habitat in tributaries, and removing barriers or transporting fish above them, is to increase carrying capacity in tributaries where habitat has been degraded or lost to barriers like dams and culverts. However, a critical uncertainty is whether restoring or reconnecting this habitat is sufficient by itself to recover native fish and wildlife populations, and whether hatchery or non-native invasive species will usurp these resources and prevent benefits to native populations. If the uncertainty is not addressed, then it could be that restored habitat often will be dominated by hatchery fish or non-native species and, therefore, be of little benefit for recovering native wild fish. Addressing whether or not transporting anadromous and resident fish around barriers will aid in recovering populations will help determine the cost-effectiveness of this approach.

[6] In this report, the Columbia River and its two main tributaries—the Snake River and the Willamette River—are considered mainstem. All sources of freshwater to any of these three rivers are considered tributaries.

Example sub-uncertainties:

2.1. Is current habitat carrying capacity sufficient to support sustainable populations of both native and hatchery fish? (See Programmatic Comments 2 and 6.)

2.2. Will any increase in carrying capacity be usurped by non-native invasive species, preventing recovery of native fish and wildlife populations?

2.3. How much does eliminating barriers (removing dams and culverts, or transporting migrating fish above dams) increase carrying capacity and contribute to recovering important fish populations?

2.4. Is the protection and restoration of watersheds and riparian/aquatic habitats sufficient to sustain fish populations during periods of unprecedented climate that cause extreme events (e.g., droughts or floods) and in watersheds declining in overall condition?

Extreme climate events are becoming more frequent (e.g., Salathé et al. 2010) and causing extreme and unfavorable habitat conditions for fish and wildlife. A highly critical question is whether restoration can provide resilience to buffer against these extremes sufficiently to sustain and recover native species of interest.

Example sub-uncertainty:

3.1. How can habitat restoration activities or hydrosystem operations modify groundwater-surface water interactions and floodplain habitats to provide refuges during extreme events and improve overall survival, productivity, distribution, and abundance of anadromous and resident native fish populations?

Hydrosystem flow and passage operations

1. How do hydrosystem operations affect fish survival (including salmonids, eulachon, sturgeon, lamprey, and other focal species)?

Information is needed to assess project compliance with mandated targets, understand impacts of management actions on fish, and understand where and when the largest sources of mortality are occurring so that corrective actions can be taken. For example, the Federal Columbia River Power System Juvenile Dam Passage Performance Standards and Metrics (NOAA Fisheries, FCRPS Supplemental Biological Opinion, section 3.3.3.2) requires an "average across Snake River and Lower Columbia River dams of 96% average dam passage survival for spring Chinook and steelhead and 93% average across all dams for Snake River subyearling Chinook." This is currently being monitored by PIT-tagging (and JSATs tagging in the U.S. Army Corps of Engineers-funded projects) juvenile salmon. Some tagged fish are detected during their downstream migration and then as returning adults, and statistical methods are used to *estimate survival probabilities, straying rates, etc. The Comparative Survival Study reports (CSS 2015) examine how juvenile survival and smolt-to-adult returns (SARs) change in response to changes in flow and spill. A life cycle model is being constructed by the CSS that models survival from eggs to spawners so that impacts on changes in survival due to management actions such as changing spill can be predicted. Without such knowledge, the consequences of management actions will be unknown and potentially ruinous for stocks*.

Example sub-uncertainties:

1.1 What is the relationship between levels of flow and spill and survival of juvenile fish through the Columbia Basin hydrosystem?

1.2. What are the effects of spill operations on returning adults that subsequently affect adult fish migration behavior, straying, pre-spawning mortality, and smolt-to-adult return ratios (SARs)?

1.3. How does the existing hydrograph affect reproductive and recruitment success for sturgeon and burbot and thus conservation aquaculture operation decisions in the Kootenai River subbasin?

2. How do hydrosystem operations affect salmon survival differently by life history type and stock (e.g., Snake River fall Chinook) thereby indicating the need for different hydrosystem operations?

Maintaining life history diversity promotes resilience. Thus, hydrosystem operations that adversely affect some life histories (e.g., yearling versus subyearling migrants) may threaten resiliency. This uncertainty will become even more critical when effects of climate change and a revised Columbia River Treaty are superimposed.

3. How does multiple dam passage versus transportation affect juvenile-to-adult survival rates for each species?

Recent studies (e.g., CSS reports) have shown that transportation benefits appear to be marginal for some stock, under certain flows at different times of the year. But other research studies indicate a potential problem with non-random sampling of fish for the transportation studies. Delayed mortality (D) is the ratio of ocean survival of Snake River fish that were transported to the ocean survival of similar fish migrating in-river. The CSS concluded that "Estimated D values for subyearling Snake River fall Chinook were below 1, for nearly all groups in the years 2006 to 2012. That was similar to patterns seen in yearling Chinook and steelhead (hatchery and wild groups) in the same years. A longer time series for subyearling Chinook would be helpful to determine if D estimates would have been higher prior to 2005 (the beginning of court-ordered summer spill) similar to the pattern seen for hatchery and wild steelhead groups that had D values that were well above 1 for several years prior to 2006." Smith et al. (2013) found that with some exceptions, the estimated benefit of transportation was usually nearly constant *throughout the season or steadily increasing for both wild and hatchery Chinook salmon. Estimated benefits of transportation for wild steelhead were relatively constant throughout the season for 8 of the 10 migration years. Hatchery steelhead exhibited more variation in patterns of transportation benefits than did wild steelhead. The reasons for the variation in results are unknown. However, Hostetter et al. (2015) indicated that juvenile bypass systems tend to select smaller fish in poorer condition compared to fish that use the spillway or turbine systems. Because the juvenile bypass system is used to select fish for transport, this may explain the negative findings of the effect of transport. Further studies on this question would benefit from incorporating multiple populations and collection locations plus multiple years to address these additional complexities.*

Example sub-uncertainty:

3.1. How does juvenile passage through multiple dams versus transportation affect adult fish migration behavior, straying, and pre-spawn mortality, and juvenile-to-adult survival rates?

4. What are the effects of water temperature at mainstem dams and reservoirs on fish passage (both juvenile and adults)?

Climate change is projected to increase water temperatures, which will impact the migration and health of fish through the Basin. What are the projected impacts and can they be alleviated by changes in operations (e.g., by providing thermal refuges for fish during periods of warm water to increase survival of returning adults)?

5. What is the feasibility of reintroducing self-sustaining anadromous fish at each federal and non-federal project that currently blocks anadromous fish from historic habitat? Specifically, what is the feasibility of implementing adult and juvenile passage at dams that currently do not have passage?

There are wide-ranging discussions in the Basin about the feasibility of reintroducing anadromous salmon and other fishes extirpated by the development of the hydrosystem. While this may be a laudable goal, there are numerous uncertainties associated with the endeavor. The extirpation of the original fish community took place many decades ago and novel biotic communities have assembled in response to new biophysical conditions. These communities are substantially different from those historically encountered and, in essence, they may be occupying nearly all the available niche space. Additionally, successful re-introduction of anadromous fishes into upper Basin areas will require adequate survival of migrating juveniles and adults through multiple dams and reservoirs in addition to potentially unfavorable conditions in the ocean. Before embarking on an endeavor to reintroduce native fishes above artificial barriers it will be necessary to evaluate the feasibility of establishing productive and resilient populations.

The key question is whether a self-sustaining population can be established above the high-head dams in the upper Basin. Trap-and-haul and other technologies can move fish, but will this support a viable population? Resolving this question has a broad spatial scope and over time could have a large impact on abundance, productivity, and diversity of anadromous fishes. Prior to dam development the upper Basin supported sustainable populations, but whether it is possible to reestablish them in the currently modified system is less clear. Although passage technologies may be transferable, the hydraulic conditions at every dam are different. Studies to address this uncertainty are planned above Chief Joseph Dam and in some Willamette and lower Columbia River tributaries.

Example sub-uncertainties:

5.1. What is the feasibility of upstream and downstream passage options for salmon and steelhead in the upper Columbia (above Chief Joseph and Grand Coulee dams)?

5.2. What approaches have been proven effective at successfully transporting juvenile and adult salmonids around high head dams (where ladders will not work) while maintaining fish viability?

5.3. Will the novel biotic communities that have assembled since barrier construction—with their predators—allow the reintroduction of productive native fish populations?

Mainstem habitat

1. Where, when, and at what frequency under different conditions do salmonids and other native species use coldwater thermal refuges in the lower Columbia and Snake rivers?

The need to identify locations of thermal refuge and how to enhance them will be increasingly critical to the preservation and enhancement of salmon in mainstem habitats under increased temperature regimes projected with climate change. For example, high water temperatures are thought to be a major contributor to the high mortality in returning sockeye salmon in 2015. The effects of climate change are already being experienced and are likely to escalate in a relative short period of time.

Example sub-uncertainty:

1.1. What would be the effects of operational changes for optimizing water temperatures and water quality for fish in shoreline and riparian habitats, as well as for wildlife in these habitats?

2. What role do changes to the historical mainstem habitat (prior to dam construction) have in changing the density-dependent responses of salmon, sturgeon, and other species (anadromous and resident)?

Understanding the carrying capacity of the current mainstem habitats for focal species is critical in assessing density-dependent responses to fish stocking and other management actions. For example, are current stocking levels exceeding current carrying capacity? This uncertainty has basinwide consequences and is applicable as long as there are dams in the river system. Furthermore, habitats may have been irreversibly changed after dam construction (see Programmatic Comment 6). If current capacity is far below historical levels, can it be increased?

3. How might operational decisions and other mainstem habitat actions maintain and improve focal populations of anadromous fish, resident fish, and wildlife?

This is an important uncertainty because much effort and money has been and likely will continue to be spent on efforts to restore habitat for focal species in mainstem habitats. Can these efforts be enhanced by operational changes? Are there operational changes that negate the benefit of habitat improvements? Are there operational changes that are more effective under different climate regimes (e.g., La Niña)? Resolving this uncertainty will be particularly important under projected impacts of climate change.

Example sub-uncertainties:

3.1. What are the impacts of hydrosystem operations on mainstem habitats, including the freshwater tidal realm from Bonneville Dam to the salt wedge? How might hydrosystem operations be altered to recover mainstem habitats?

3.2. What should be the magnitude and timing of restored flows, ramping rates, and temperature regimes for the free-flowing segments of the river?

4. How much spawning and rearing habitat is available to white sturgeon above and below Bonneville Dam under a range of actual operational conditions? How do these conditions differentially affect spawning success and juvenile growth and survival to the recruitment stage and their entire lifespan?

Nearly all white sturgeon habitat in the Basin is in mainstem reaches of the Columbia and Snake rivers and major tributaries. As a result, every life stage of this species is impacted by conditions in the mainstem. This is an especially critical uncertainty above Bonneville Dam where environmental conditions have led to a lack of recruitment. Managers' actions to propagate, translocate, or otherwise increase the number of white sturgeon will not be successful if there is inadequate mainstem habitat—and connectivity between habitats—in which they can grow and mature. Also see the Population Structure and Diversity section of this report for other uncertainties related to white sturgeon.

Example sub-uncertainties:

4.1. How do water temperature fluctuations and seasonal changes resulting from Columbia River hydrosystem operations affect growth, survival, and habitat use of white sturgeon?

4.2. What are slough characteristics that provide benefits to white sturgeon survival during early life history stages and recruitment? Are there potential slough restoration sites that would provide benefits to white sturgeon?

4.3. What is the relationship between recruitment failure and habitat conditions for white sturgeon? Can natural recruitment of white sturgeon be improved by operational changes in water management?

Estuary, plume, and ocean

1. How much do specific factors impact growth, fish condition, residence time, age at maturation and survival of focal fish species (anadromous salmonids, white sturgeon, Pacific lamprey, eulachon) in the estuary, plume, and ocean?

Quantifying the impact of specific factors on focal fish species in the estuary, plume, and ocean will lead to more efficient and effective management and restoration actions throughout the Basin. The impacts of some factors (i.e., avian predation on Chinook and steelhead smolts in the estuary) are relatively well researched, whereas little is known about the impacts of other factors (i.e., climate change, hypoxia, acidification, fish propagation, contaminants, disease, and invasive species). It is important to understand these impacts across the continuum of habitats used by each species. For example, factors impacting growth in the estuary may also affect subsequent growth and survival in the plume and ocean. Monitoring estuary and ocean survival is difficult, but other biological indicators such as fish growth, condition, residence time, and age at maturation may be more feasible to monitor. Research addressing this critical uncertainty would continue to build upon a growing body of scientific information on factors impacting estuary and early marine survival of juvenile salmonids. The uncertainty is relevant to all focal species, and the results would be useful for further development of predictive (run forecasting) and life-history models. This critical uncertainty is modified from the 2006 Research Plan; see Part 2, CU #19, for a discussion of progress made toward addressing this uncertainty.

Example sub-uncertainties:

1.1. To what extent can predictive models be used to evaluate the potential impacts of hydrosystem projects on estuary, plume, and coastal marine habitats and their biota?

1.2. How large are density dependence effects for salmonids in the estuary and ocean, including the influence of hatchery fish and/or invasive species (e.g., American shad juveniles)? (See Programmatic Comment 6.)

1.3. How do climate change, hypoxia, and ocean acidification affect survival of focal fish species (anadromous salmonids, white sturgeon, Pacific lamprey, eulachon) in the estuary, plume, and ocean?

2. What are the responses of focal species (anadromous salmonids, white sturgeon, Pacific lamprey, and eulachon), life history types, and populations to alternative restoration actions and locations in the estuary, mainstem, and tributaries that will best inform management decisions?

The lack of information on responses of focal species, life history types, and populations to alternative restoration actions and locations throughout the Basin is a major information gap. Answers to this question will have direct application to guide future protection and restoration work. The scale of data collection is presently insufficient throughout the Basin to address relative benefits of restoration by life stage and habitat type. This uncertainty is relevant to all focal species, and the results would be useful for further development of predictive capabilities (e.g., run forecasting) and life-history models. This critical uncertainty is modified from the 2006 Research Plan; see Part 2, CU #17, for a discussion of progress made toward addressing this uncertainty.

3. How can we efficiently and effectively manage and restore estuarine habitat to increase the carrying capacity of the estuary for salmonids and other focal species (anadromous salmonids, white sturgeon, Pacific lamprey, and eulachon)?

This uncertainty is the bottom-line issue for this theme because results will assist the Council in working with partners in the estuary to establish clear biological objectives and indicators that prioritize future management and restoration actions. This uncertainty focuses specifically on carrying capacity, which is defined in the Program as "The number of individuals of one species that the resources of a habitat can support. That is, the upper limit on the steady-state population size that an environment can support. Carrying capacity is a function of both the populations and their environments." At present, we lack empirical evidence that management and restoration efforts in the Columbia River estuary have increased the carrying capacity of salmonid populations. The conceptual approach currently used by partners to evaluate the overall effectiveness of restoration efforts in the estuary does not directly involve measures of fish population dynamics (e.g., carrying capacity) that are used elsewhere in the Basin (ISAB 2012-6, 2014-1). This broad question addresses core goals of the Program to restore ecosystem function, enhance conditions for salmonids, and improve and expand habitat function, structure, and complexity in the estuary. Addressing this question will also contribute to the wild fish strategy in the Program, which states as a general measure that the Council will consider the needs of wild fish in all facets of its fish and wildlife program, including carrying capacity and habitat actions. Many sub-questions can be derived from this overarching question.

Example sub-uncertainties:

3.1. What tidal freshwater, estuary, and plume habitats and their biota are most important to focal species (anadromous salmonids, white sturgeon, Pacific lamprey, eulachon)?

3.2. What ocean habitats and their biota are most important to survival of each focal species (anadromous salmonids, white sturgeon, Pacific lamprey and eulachon)?

Contaminants

1. What are the distributions, uses, and concentrations of toxics, including emerging contaminants, in the Columbia River Basin, and what are their trends over time?

This is the fundamental uncertainty for this theme. Although it may be difficult to obtain data at sufficient temporal and spatial scales to fully resolve the uncertainty in the near term, it forms a foundation for understanding the magnitude of the threat and formulating approaches for tackling other contaminant-related uncertainties. Contaminants are not easily detected, so managers may unknowingly try to restore habitat in need of substantial clean-up. This critical uncertainty is from the 2006 Research Plan; see Part 2, CU #34, for a discussion of progress made toward addressing this uncertainty.

The proliferation of artificial chemicals in the Basin was recently identified by the ISAB as one of the highest priorities for resolution (ISAB 2011-1, ISAB 2013-1). The most recent tally of pesticide use (average for 1999-2004) lists 182 chemicals, with an aggregate application rate of ~46,000 metric tons (~50,000 U.S. tons) of active ingredients annually; these are concentrated mostly in agricultural lands along water courses (See Programmatic Comment 2; Figure 2; ISAB 2001-1). In the 2013 ISAB report, specific recommendations were made for addressing chemicals and contaminants:

(1) Actively investigate the impact of chemicals on restoration activities by fully implementing a water quality program. This initiative will require working partnerships between federal and state agencies as well as initiating modeling of how climate and temperature affects contaminant toxicity for all parts of the Basin.

(2) Work diligently with other regional agencies to implement the interagency Columbia River Basin Toxics Reduction Action Plan (US EPA 2010).

(3) Update the plan regularly, so that current and future chemical inputs to the system can be addressed in a timely fashion, before they become even more serious problems. The nature of the issue dictates that this will be a large, ongoing, and collective regional effort.

A new, interactive mapping tool shows predicted concentrations for 108 pesticides in streams and rivers across the United States and identifies which streams are most likely to exceed water-

quality guidelines for human health or aquatic life. It also provides information on probabilities of exceeding established benchmarks. It is based on Watershed Regression for Pesticides (WARP) models as part of the National Water-Quality Assessment (NAWQA) Program. A complete description of the development and performance of the WARP models is provided in Stone et al. (2013); additional information is available at http://cida.usgs.gov/warp/home/. This mapping tool should be a useful resource in watershed assessments and in the identification and planning of restoration strategies and individual project treatments.

Example sub-uncertainty:

1.1. What are the impacts of different hydrologic scenarios and management actions (e.g., dam operations and flow management) on contaminant distributions and transfer of contaminants to food webs?

2. How do toxic substances, alone and in combination, affect fish and wildlife distribution and abundance, survival and fitness, and productivity in the Columbia River Basin?

Addressing this uncertainty will require knowledge of the distribution of contaminants and their effects on biological resources in the Basin. If unchecked, the harmful effects of toxic substances could potentially negate mitigation and restoration efforts. Addressing this uncertainty will require a high level of integration and collaboration with state and federal agencies. This critical uncertainty is from the 2006 Research Plan; see Part 2, CU #35, for a discussion of progress made toward addressing this uncertainty.

Example sub-uncertainties:

2.1. What are the cumulative and/or synergistic effects of multiple toxic contaminants, particularly pesticides, on riparian insects and other organisms that impact the carrying capacity of the Columbia River ecosystem (including estuarine, coastal ocean and riverine habitats), as well as interactions between these chemicals and non-chemical stressors?

2.2. How do food web transfer, sediment transport, and biological effects of emerging and legacy organic contaminants under current management regimes affect key Columbia River species, the success of restoration projects within the Basin, and human health (i.e., the success of harvest mitigation)?

2.3. What levels of chemicals of emerging concern (CECs)[7] impact the health of focal species including Pacific lamprey, white sturgeon, and salmonids?

[7] "A contaminant may be 'emerging' based on one or more of the following (1) the compound's recent identification in the environment, (2) challenges in trying to regulate its unknown risks, (3) concern over its presence and potential effects, or (4) as a matter of scientific interest in a compound about which little or nothing is known (Arp 2012). A particular CEC may pose a real or perceived threat to human health or the environment,

Programmatic Comment 2. Water quality

Fish, wildlife, and human populations in the Basin and elsewhere in the United States are exposed to an ever-growing variety of pollutants as a result of increasing urbanization, industrialization, and agricultural development (Figure 2).[8] Human communities use and dispose of thousands of different chemicals, pharmaceuticals, and personal care products. Many end up in aquatic systems where they persist, affect organisms and food webs, and, in some cases, accumulate in consumers near the top of the food web. It is well documented that the lower Columbia River and its tributaries contain concentrations of toxic pollutants that are harmful to fish and wildlife. Contaminants of greatest concern in the late 1980s and early 1990s included dioxins and furans, heavy metals, polychlorinated biphenyls (PCBs) and organochlorine pesticides such as DDT (Tetra Tech 1996). Today there is continuing and growing concern about persistent pollutants coming from a wide variety of sources, especially those that linger in the environment and are known to affect the health of humans or the aquatic community. Further, there is also growing concern about "emerging contaminants," a group of potentially harmful chemicals (including flame retardants and pharmaceuticals) for which only limited information is available.

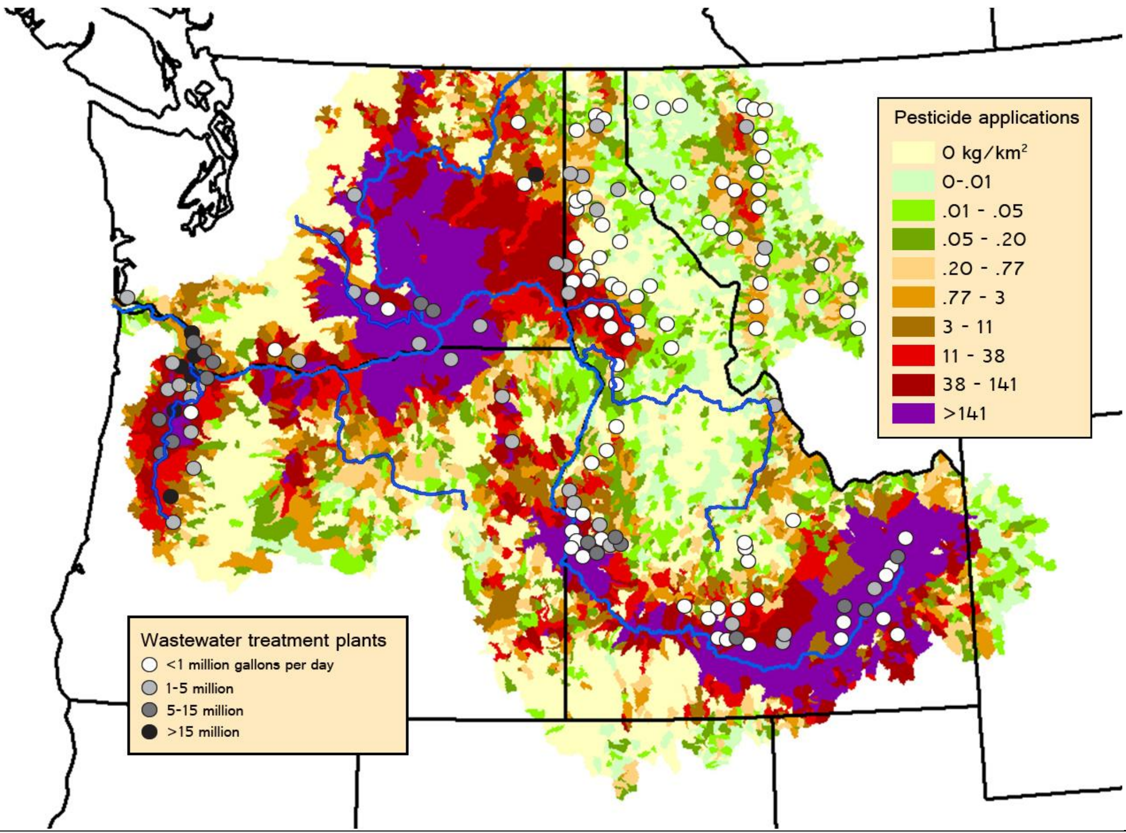
Little attention has been paid to the effects of contaminants on fish production and survival, even though pollutants have been recognized for many years as a problem in the Columbia River and its tributaries, especially for species positioned higher in the food web (ISAB 2011-1). The vulnerability of the estuary and the coastal ocean communities to the accumulation of contaminants is especially worrisome because of their spatial positions in the watershed. Contaminant-related declines in populations of fish-eating species often lead, after the fact, to further study of contaminants in the prey fish species. However, studies of contaminants in invertebrate species, many of which are the first components of the food web to accumulate contaminants, are extremely rare in the Basin. The collective impacts of contaminants continues to grow, and there is an obvious need to quantify and map the spatial and temporal patterns of these chemicals; to assess their transfer, accumulation, and persistence; and document their impact on native organisms and on the carrying capacity of the Columbia River ecosystem for juvenile salmonids. The Council has an opportunity to take an active role—through cooperation with regional partners—to ensure monitoring and mapping of toxic contaminants, evaluate their effects on fish and wildlife, and ameliorate their collective impacts.

---

but there are no currently published health standards for most CECs, because the science has not advanced sufficiently to provide a basis for assessing toxicity." US EPA 2014 page 6. Arp, H.P.H., 2012, Emerging contaminants: Environmental Science and Technology, 46: 4259-4260.

[8] The amounts and diversity of chemicals in use are both stunning and a matter of great concern, with almost 454,000 metric tons/year of pesticides applied in the United States since 1980 (Gilliom et al. 2006, Grube et al. 2011). A great diversity of pesticides is used (http://water.usgs.gov/nawqa/pnsp/usage/maps/), and pesticides have been detected in every region of the United States where surface water has been analyzed, including the Columbia Basin (Larson et al. 1997). In watersheds with agricultural or urban land use, stream organisms are likely to be exposed to mixtures of multiple pesticides (Gilliom et al. 2006). Besides pesticides, numerous studies have reported a variety of manufactured and natural organic compounds such as pharmaceuticals, steroids, surfactants,

Figure 2. The Columbia River Basin has undergone substantial transformation through the application of pesticides (246 compounds evaluated; average 1999-2004; data obtained from USGS, National Water Quality Assessment Project) and construction of >169 wastewater treatment plants.



Climate change

1. How will the long-term climate trends predicted for the Columbia River Basin and the northeast Pacific Ocean affect fish and wildlife in the region?

Some modeling has been done, but future research will be an ongoing process of fine-tuning climate models and applying those models to hydrology, habitat phenology, and biota. This

flame retardants, fragrances, and plasticizers, especially in waters in the vicinity of municipal wastewater discharges and livestock agricultural facilities (Focazio et al. 2008). In addition, of the more than 6,350,000 mt of sewage sludge (dry weight) produced in the United States in 2004, about 50% was applied to land as fertilizer or soil amendment, and 45% was disposed of in landfills or as landfill cover (NEBRA 2007). Terrestrial environments can offer effective biological, physical, and chemical attenuation of manmade pollutants, but they also act as routes of chemical migration into both surface and groundwater from biosolid runoff and leachate (McClellan and Halden 2010).

question provides a broad base under which researchers and others can define more specific topics. The ISAB and ISRP believe that the sub-uncertainties associated with this broad question are among the most critical climate change uncertainties. For the Program to be successful over the long term, special attention needs to be paid to two primary aspects of water: (1) maintaining reliable quantities and (2) consistent high quality. It is important to note that quality encompasses a broad variety of issues (see Programmatic Comment 3). This critical uncertainty is derived from the 2006 Research Plan; see Part 2, CU #33, for a discussion of progress made toward addressing this uncertainty.

Example sub-uncertainties:

1.1. What food web effects are associated with long-term climate trends predicted for the Columbia River Basin?

1.2. How secure are surface and ground water sources as aquifers are being depleted because of multiple and competing uses?

2. What strategic actions, alone or in combination and at what spatial and temporal scales, could help ameliorate increased water temperatures, decreased summer river flows, changes in upland plant communities, and other ecosystem changes due to climate changes that will impact fish and wildlife?

This was identified as a top priority in the climate change theme. A moderate amount of progress has been made addressing climate-associated effects on temperature and flow, but there has been little progress in modeling ecosystem changes. This critical uncertainty is derived from the 2006 Research Plan; see Part 2, CU #33, for a discussion of progress made toward addressing this uncertainty.

In the summer of 2015, fish kills in the Basin due to increased, water temperatures in streams made the national news. Given predictions of a changing climate, with increased temperatures and generally reduced snow packs and summer stream flows and increasing levels of land development and resource use, the extent and severity of fish kills are likely to increase (see Programmatic Comment 3). Additional attention is needed to better document and quantify this issue. This will allow a determination whether specific response strategies are needed as part of the Program and/or whether additional research is necessary. Managers will require this information to develop strategies for adapting to climate change. For example, when selecting areas for habitat restoration, managers might first consider areas likely to provide thermal refuges for aquatic species.

Example sub-uncertainties:

2.1. What are the potential effects of climate change on river hydraulics, temperature, and sediment movement in tributaries and mainstem reaches of the Columbia River Basin?

2.2. How could integrated ecological monitoring be used to determine how climate change affects fish and wildlife and the freshwater, estuarine, ocean, and terrestrial habitats and ecosystems that sustain them?

2.3. Are the Program's habitat restoration actions and hatchery facilities able to effectively respond to rapid changes in water availability and quality?

2.4. How might climate change affect the success of salmonid reintroductions, supplementation or recovery efforts, particularly since warmer waters may favor other species, especially non-natives?

Programmatic Comment 3: Water security

Water security is defined as "*an acceptable level of water-related risks to humans and ecosystems, coupled with the availability of water of sufficient quantity and quality to support livelihoods, national security, human health, and ecosystem services*" (Bakker 2012). Water security is challenged by a variety of environmental and human conditions related to water supply (e.g., flooding, engineered infrastructure, pollution, hydrologic variability due to climate change) and conditions related to water demand (e.g., population growth and changes in preferences, policy, and management). Water security can also be compromised at the level of the individual, for example from an inability to acquire water (e.g., due to poverty or loss of rights). Understanding the causes of and potential remedies for water scarcity requires understanding a complex social-ecological system and therefore requires an understanding of both biophysical and socio-economic sciences, including knowledge of water law and other institutions related to management and governance. Approaches to enhance water security and reduce water scarcity include demand-side approaches (conservation, efficient pricing, regulations, technology, information, and altering expectations) and supply-side approaches (infrastructure changes, agreements across jurisdictions, and conflict resolution efforts). Water security issues that could affect the success of the Program include water quality and quantity issues; tradeoffs between water availability and energy production; governance issues between countries, states, tribes, and other stakeholders; and threats to water supply and delivery due to climate change.

Restoration practitioners in the Basin have found water security to be a particularly difficult issue to address. One reason for this is that water security is tied to water law, where there exists a complex intersection of state law, federal regulations, multiple jurisdictions, tribal rights, and international treaties. More planning is required to achieve project objectives under conditions of rapid, landscape-scale changes in water availability and quality. Successful restoration must operate under the basic premise of ecosystem conditions being non-stationary, develop the ability to forecast future ecosystem conditions and rates, and then align implementation efforts with emerging ecosystem conditions including the influences of future socioeconomic changes. Without such planning components for water, restoration practitioners are limited in their ability to meet water availability and quality challenges associated with climate change, altered hydrologic regimes, and land-use change that realign basic water processes. Anticipating future changes in water security is central to a successful Program in this regard.

The capacity of habitats and hatcheries to produce high quality fish and meet mitigation goals is strongly influenced by available water supply and its quality. Climate change, augmented with expanding water demand from urbanization, industrial development and agriculture, will likely increase variability and result in more frequent and larger magnitude flooding and droughts, and greater fluctuations in temperatures. In addition, growing populations, higher incomes, and technological innovations will increase energy demand in the region, put added pressure on environmental water supplies, and have impacts on hydropower production that are difficult to predict.

Non-native species

1. To what extent is the viability or abundance of native fish and wildlife species in the Columbia River Basin jeopardized by non-native species?

This overarching question reflects advice in both the Program and the ISAB non-native report (ISAB 2008-4).Both documents emphasize that the increasing presence of non-native species, potentially exacerbated by continued legal and illegal introductions and climate change, is imperiling native species recovery efforts. Detrimental effects on native species are resulting from predation, competition for food, interbreeding, disease transmission, food web disruption, and physical habitat alterations. Non-native species change biotic interactions, create novel ecosystems, and have the potential to undermine otherwise successful habitat restoration efforts. Effects of non-natives on the native fauna are seldom well understood, are typically difficult to predict accurately, and may be recognized only after the native species are in steep and sometimes irreversible declines in abundance and recruitment. Once non-native species are established, efforts to remove them are typically unsuccessful. A key principle outlined in the Program is to "prevent, monitor, control, and stop or minimize the spread of non-native and invasive species where these pose a threat... to native fish, or to wildlife species."

In many cases, habitat conditions that originally favored native species no longer exist. Managers, thus, may have a difficult choice between attempting to manage for the native species poorly suited to the new conditions or compromising and providing fisheries with popular non-natives that are better suited to available habitat. In systems containing established non-native species, an important aspect of the decision-making process is determining whether the return to a previous state, dominated by native species, is feasible or whether there is a need to develop new goals and objectives to deal with the novel ecosystems. Management and policy decisions must consider not only the ecological aspects of non-native species on native species but the social issues and perceptions of stakeholders and the public. Among non-native fishes, the most problematic species in terms of policy development are those already introduced into a *basin and that have perceived benefits (e.g., game fish) that militate against eradication or reduction actions ([ISAB 2008-4](#)). Managing such problematic species entails not only attempting to control their distribution, abundance and productivity, but also considering their effects on often-declining native species, the continually evolving landscape, and divergent, rapidly shifting public opinion. The current inconsistent management strategy for non-native, problematic species such as lake trout, walleye, northern pike, smallmouth bass, largemouth bass, and other panfishes (e.g., Centrarchidae) reflects how those species are perceived to be harmful to humans and other species, but also reflects ambiguous, and sometimes strongly conflicted, attitudes by the public and co-managers about the value of those species. Future research should include not only interactions among fishes, but among fish and other fauna and flora. Issues involving non-native pathogens and hosts also need to be better understood. Research also must consider effects of non-native aquatic, terrestrial and riparian species on riparian and terrestrial native species recovery efforts. Various management interventions and restoration initiatives for controlling or eradicating invasive non-native species should be implemented and monitored. This critical uncertainty is derived from the 2006 Research Plan; see Part 2, CU #37, for a discussion of progress made toward addressing this uncertainty.*

2. What are the primary pathways of introduction of invasive and non-native species, and what management actions could limit new introductions or mitigate the impact of invasive species?

This overarching question also comes from the Program and the ISAB's non-native report (ISAB 2008-4). Non-native fish species introductions have resulted from both deliberate and unintentional human activity. Introductions of non-native fishes have been initiated for perceived aquaculture benefits, as well as to develop or enhance fisheries, and fill vacant niches as in blocked areas above dams. Although many historical introductions of non-native species were initially made by state and federal agencies, in recent years more have been illegal, unintentional, and not approved by agencies. There is a need for more outreach on species identification, so that non-natives may be recognized more readily in surveys and by the public. Identifying the most likely introduction pathways, both in specific situations (e.g., in a particular water body) and vectors (e.g., the pet trade, on trailers, boat hulls or in ballast) is crucial to preventing and curtailing introductions. This critical uncertainty is derived from the 2006 Research Plan; see Part 2, CU #38, for a discussion of progress made toward addressing this uncertainty.

Predation

1. To what extent is the viability or abundance of native fish and wildlife populations in the Columbia River Basin jeopardized by predation?

This uncertainty is highly relevant to the Fish and Wildlife Program vision regarding the abundance, diversity, and resilience of focal species. Considerable theoretical and some historical knowledge exist about the long-term dynamics of native predators and their co-evolved prey. However, predicting how predators will impact prey populations is particularly difficult when *other factors affecting the abundance or vulnerability of the prey are changing beyond historical norms (see Programmatic Comment 4). The ISAB has not comprehensively reviewed the impacts of predation on Columbia River salmon, but it has summarized some existing knowledge in its reports on food webs ([ISAB 2011-1]) and density dependence ([ISAB 2015-1]).*

Example sub-uncertainty:

1.1. What proportion of adult salmon and white sturgeon are killed by sea lions (and other marine mammals) during their upstream migration below Bonneville Dam?

Programmatic Comment 4. Predators as part of the ecosystem

The role of predators in maintaining community structure and ecological diversity is often poorly appreciated. The fact that a typical Pacific salmon lays thousands of eggs, of which the vast majority likely die during incubation or are eaten at later life stages, indicates that salmonids have evolved to survive as prey species within a complex food web. Modern ecological thinking that focuses on the food webs involved in nutrient recycling and energy flow in ecosystems (e.g., ISAB 2011-1) often cautions against removal of predators (Patton 2011). In part this is due to ethical concerns, especially when the sole justification is competition between predators and humans for the same prey (Boyce and Byrne 2007). The practice seems better justified, or at least more acceptable, when it is used to control an exotic species of predator (Harding et al. 2001) or to protect a threatened or endangered species (Dekker 2006). However, controlling predator populations to reduce predation on a threatened or endangered species may be difficult to achieve.

Because predators reduce their feeding rate as they become satiated, predation mortality on a prey population is typically depensatory, meaning that the proportion eaten is higher when few prey are present than when many prey are available. However, the typical depensatory functional response of individual predators can be offset to some extent by an increase in the number of predators due to aggregation in the short term or increased predator reproduction and abundance in the long term. Thus, large releases of hatchery fish can affect predation of natural-origin fish indirectly, by influencing the behavior and dynamics of predator populations.

Predation on adult salmonids during upstream migration (e.g., by pinnipeds, especially sea lions) is of particular concern because it may reduce the potential spawning population more than an equivalent rate of predation at earlier life stages. Losses to predators early in the salmonid life history (e.g., from bird and fish predation) might be mitigated by lower (i.e., compensatory) mortality during later life stages, especially if predators selectively remove the most vulnerable individuals. By the time adult salmon enter the Columbia River estuary, they have already survived numerous threats in both freshwater and marine environments, and all are potentially valuable for harvest or spawning. Recent tagging studies by NOAA indicate that after accounting for fishing mortality and impacts from sampling gear, the weighted mean annual survival of spring Chinook migrating upstream from the Lower Columbia estuary past Bonneville Dam has declined steadily from 90% in 2010 to 69% in 2013 (Wargo Rub et al. 2014)—coincident with a local increase in pinniped abundance. Even so, the escapement goal of spring Chinook counted at Bonneville Dam (115,000 fish) has been met or exceeded from 2008 to 2015 despite indications that predation by pinnipeds is increasing.

Depensatory mortality is destabilizing and may further accelerate the decline or inhibit the recovery of populations reduced to low abundance. However, it is important to recognize that depensatory mortality from predation in particular life stages (i.e., in components of the life cycle) can be overwhelmed by compensatory mortality at other life stages, so that the effects of density over the entire life cycle remain compensatory. Actions that increase population productivity by improving, for example, habitat quality for spawning, incubation and early juvenile rearing, or by alleviating hydrosystem impacts during migration, can help a population escape the potentially destabilizing effects of depensatory predation at low density. None of the life-cycle recruitment relationships for Columbia River salmon populations examined to date exhibit signs of depensation (ISAB 2015-1). Thus, density dependence over the entire life cycle appears to be strongly compensatory even though depensatory mortality likely occurs at some life stages. Density dependence over the entire life cycle is what really matters for determining a population's overall productivity and resilience.

2. How effectively can undesirable impacts of predation be ameliorated by management actions including hydrosystem operations, habitat modifications and predator population control?

Predators respond behaviorally, ecologically, and evolutionarily to foraging opportunities, such as those created by hydroelectric dams that modify the migratory corridors of juvenile and adult salmon, and the release of large concentrations of naïve hatchery-reared smolts. Contemporary predator populations are probably supported to some degree by the relatively constant annual releases of about 140 million salmon and steelhead from hatcheries. The feasibility and cost effectiveness of predator control programs are questionable except in relatively restricted areas where prey are especially vulnerable and predator impacts are concentrated (e.g., near bird colonies and tailraces). Benefits of reducing smolt mortality due to piscivorous birds and fish might be largely lost through density dependent (i.e., non-additive) mortality at later life stages (ISAB 2015-1; see Programmatic Comment 5). Such compensatory effects are less likely later in life, and predation during upstream migration is likely to have more impact on adult abundance than an equivalent rate of predation at earlier life stages. Predator control programs can also have counter-intuitive and unintended consequences for both the target populations and other predator and prey species (see Programmatic Comment 5).

Example sub-uncertainties:

2.1. To what extent can the productivity or viability of salmon populations be increased by management actions to reduce avian and fish predation on smolts during the downstream migration versus actions to reduce marine mammal predation during the upstream migration below Bonneville Dam?

2.2. How does the cost-effectiveness of actions to control predator populations compare to that for alternative actions (e.g., flow and habitat modifications, hatchery supplementation) to increase the productivity or viability of natural salmon populations?

2.3 How do hatchery releases (that determine the total density of prey available to predators) affect the rate of predation on natural-origin salmon (both smolt and adult stages), and in particular, the productivity of natural ESA-listed salmonid populations?

Programmatic Comment 5. Predator control

Recent proposals to cull predators of salmon in the Columbia River estuary (e.g., double-crested cormorants and sea lions) have renewed controversy about the merits of such predator controls. Lessard et al. (2005) describe the extreme uncertainty associated with any policy aimed at controlling complex interactions that determine extinction risk for focal species and argue that such policies should be treated as management experiments with careful treatment (e.g., control comparisons and monitoring).

Despite the long history and prevalence of predator control programs, their biological and economic effectiveness have seldom been quantitatively evaluated in an effective way. Past experience indicates that predator control is best used only to solve a local and temporary perceived problem and is generally not feasible over a wide geographic area for both biological and economic reasons (Patton 2011). Successful cases have typically required a sustained effort and a large proportional reduction (>50%) of the predator populations; moreover the benefits typically disappeared rapidly in the absence of control (Bowen and Lidgard 2011). Predator control requires a long-term management strategy. Yet few programs to cull predators of aquatic species have had clearly articulated, measurable objectives for prey population recovery or increase, and the success of such programs has seldom been evaluated with respect to those objectives (Bowen and Lidgard 2011).

Given the complexity of food webs in ecological communities, predator control programs, like other “command and control” management approaches, can have counter-intuitive and unintended consequences for both the target populations and other predator and prey species. For example, culling of top predators may improve conditions for other intermediate level predators or exotic species that have been prevented from prospering by high predator abundance (Carpenter et al. 1995, Yodzis 2001). Predators respond behaviorally, ecologically, and evolutionarily to foraging opportunities, such as those created by hydroelectric dams that modify the migratory corridors of juvenile and adult salmon, and the release of large concentrations of naïve hatchery-reared smolts. Thus, as a strategy for recovering depleted populations, a focus on first maintaining a diversity of habitat seems more in keeping with the “resilience thinking” approach recommended by the ISAB (ISAB 2011-4, 2013-1) and acknowledged in the current Program.

Fish propagation

1. What is the relationship between basinwide hatchery production and the survival, fitness, and growth of naturally produced fish in freshwater, estuarine, and ocean habitats?

Greater knowledge of the various ways in which hatchery fish interact, both directly and indirectly, with natural origin fish is needed to evaluate the cumulative effects of fish releases from the Basin's hatcheries. Prospective management actions designed to lessen the cumulative impacts of hatchery fish become possible once the locations, life stages, types of impacts and their potential consequences have been identified. For example, the goals and size of supplementation programs could be regulated by estimating juvenile and adult carrying capacities in the subbasins where hatchery fish occur. It is unclear, however, if density-dependent considerations have been used or will be used to guide supplementation efforts in the Basin (See Programmatic Comment 6). Uncertainties also exist about the ability of segregated or integrated hatchery programs to meet adult production and harvest goals. This critical uncertainty is from the 2006 Research Plan; see Part 2, CU #6, for a discussion of progress made toward addressing this uncertainty.

Example sub-uncertainties:

1.1. What is the cost, by life stage, to natural populations from competition, predation (direct and indirect), and disease caused by interactions with hatchery-origin juveniles and from harvest in fisheries targeting hatchery-origin adults?

1.2. Can hatchery production programs meet adult production and harvest goals (integrated and segregated) while protecting naturally spawning populations?

Programmatic Comment 6. Density dependence

Density dependence is evident in most of the ESA-listed salmon populations examined, and it is strong enough to constrain their recovery (ISAB 2015-1). Studies conducted on the ESA-listed populations showed that returns of natural origin salmon were often less than the abundance of parent spawners (i.e., Recruits per Spawner (R/S) < 1), suggesting that the spawning population was not self-sustaining. This finding was surprising because density dependence, while present in most animal populations, is typically weak (i.e., does not constrain population growth) when abundance is low.

Density dependence information should be used throughout the Basin to inform and guide (1) recovery of depleted salmon populations, (2) harvest management, and (3) hatchery supplementation efforts (ISAB 2015-1). For example, strong density dependent growth when density is low during the rearing stage signals a need for restoration actions to improve growth. Density dependence information should be used to guide Program projects because it increases the effectiveness and efficiency of restoration actions and helps identify limiting factors. Also, when evaluating fish responses to restoration actions, density effects on key metrics such as growth and survival must be considered—otherwise the findings may be misleading.

Hatchery and harvest management would be improved by using density dependence relationships (stock-recruitment curves; see Programmatic Comment 7: Brood Tables) to identify (1) the range in spawning escapement needed to enable the potential for maximum returns in the future (given current conditions), and (2) the appropriate level of hatchery supplementation with both juvenile and adult salmon. Studies in the Basin indicate total spawners in some watersheds currently exceed the capacity of the watershed to support their progeny (i.e., R/S < 1), indicating the need for restoration actions to improve capacity and productivity of the habitat. When habitat capacity is exceeded, additional "surplus" spawners lead to few if any additional progeny. Many of these populations are supplemented with a large proportion of hatchery-origin spawners (pHOS).

The presence of density dependence leads to an important management decision that requires further research: should "surplus" hatchery fish be harvested to benefit sport and commercial fishers and the natural population (i.e., by reducing pHOS and enabling potential adaptation of the natural population to the local environment), or should spawning of "surplus" hatchery fish be encouraged as a means to potentially increase future capacity of the watershed to support salmon (e.g., by increasing input of marine-derived nutrients)? The first option is supported by the HSRG (2015) and is discussed by the ISAB (2015-1). Regarding the second option there are no studies that evaluate the extent to which surplus hatchery fish might markedly increase the future capacity of the stream to support salmon, although studies indicate additional carcasses (i.e., nutrients) might enhance growth of riparian vegetation and aquatic invertebrate production, and spawners are needed to maintain or enhance gravel quality by dislodging redd-clogging sediments. Alternatively, if nutrient loading was a primary factor affecting low productivity and capacity, could carcass analogs or re-distribution of fish spawned in hatcheries be used to increase nutrient loading rather than allowing surplus hatchery salmon to spawn in the rivers (Kohler et al. 2012, 2013)?

2. What is the magnitude of any demographic benefit to the production of natural origin juveniles and adults from natural spawning of hatchery origin supplementation adults?

It is not yet clear if hatchery supplementation provides a lasting demographic benefit to wild populations. Such appraisals require pre- and post-project reference streams, infrastructure to sample juveniles and adults, and genetic analyses to ascertain the pedigree of natural origin fish. Additionally, a suite of factors—including density-dependent effects, location of hatchery releases, habitat conditions, age and size of hatchery adults, spawning locations of hatchery fish, and genetic alterations to hatchery fish caused by domestication—can influence whether a hatchery program will provide a lasting demographic benefit to a natural population. Research is needed to unravel the relative importance of these factors in areas where supplementation has occurred. Results from these studies would help determine the level of supplementation that is appropriate for a subbasin on a species-specific basis. Additionally, in several subbasins hatchery supplementation is being used to reintroduce salmonids into areas where original populations *were extirpated. Monitoring and evaluation programs are needed to track the abundance, local adaptation, and straying rates of the reintroduced fish as well as their potential impacts on local biota. This critical uncertainty is from the 2006 Research Plan; see Part 2, CU #3, for a discussion of progress made toward addressing this uncertainty.*

3. What is the potential role of lamprey propagation and translocation as a way to mitigate for lost lamprey production when passage and habitat improvements alone are insufficient to restore lamprey populations? Specifically, can artificial propagation be used to supplement and restore depressed populations of Pacific lamprey?

Artificial culture is being explored as a possible option to restore Pacific lamprey abundance and distribution. Many questions remain about the methods that should be used to artificially produce juvenile Pacific lamprey, particularly during the post-hatching and early rearing periods. Translocation or the capture of adult Pacific lamprey at lower river sites and subsequent release into up-river locations is also being investigated as a recovery strategy. Research, is needed to refine adult release locations and to determine the habitat features and environmental conditions necessary to make translocation a successful strategy. Some investigators have hypothesized that Pacific lamprey may not always home to natal river basins, such as the Columbia River. Thus, a fundamental uncertainty associated with translocation and artificial culture is whether these recovery strategies will have any effect on the number of adult Pacific lamprey returning to the Columbia River. Additionally, outbreeding caused by translocation could threaten local adaptations that are not yet recognized. Genetic analyses and sampling at sites such as Bonneville Dam may help answer these questions.

4. What are the potential impacts on wild sturgeon from mixing of genetic stocks as part of broodstock and larval fish rearing mitigation efforts?

Five population units of white sturgeon are distinguished in the Columbia River: Lower Columbia, Mid-Columbia, Snake, Upper Columbia, and Kootenai. The Upper Columbia, Kootenai, and Snake population units are at risk because natural recruitment is sporadic and inadequate. These three population units span the areas where supplementation and translocation will take place. Typically just a few white sturgeon are used as broodstock in hatchery programs because of difficulties in capturing and maintaining maturing broodstock and achieving synchronous maturation. These constraints, along with low or non-existent natural recruitment, mean that genes from hatchery fish are likely to be disproportionately represented in future generations. Translocation of adults may also reduce genetic diversity if the population units they are introduced into have small natural spawning populations. The capture and subsequent rearing of naturally produced larvae is a promising new approach to white sturgeon conservation. Analyses have shown that naturally produced larvae originate from multiple parents and are genetically diverse. This is a new method, so refinements in where, when, and how to collect larvae plus how best to rear and release them are needed. Among hatchery propagation, translocation, and capture of naturally produced larvae, the latter appears to be the best strategy for maintaining genetic diversity. Uncertainties, however, about the genetic consequences of all of these *approaches on wild sturgeon populations exist. To resolve them, it will be important to periodically monitor the genetic diversity of the white sturgeon population units where sturgeon recovery efforts have taken place.*

5. What are the range, magnitude, and rates of change of natural spawning fitness of integrated (supplemented) populations, and how are these related to management rules, including the proportion of hatchery fish permitted on the spawning grounds, the broodstock mining rate, and the proportion of natural origin adults in the hatchery broodstock?

Because supplementation of salmonid populations is a widely used management strategy its effects on natural populations need to be understood. Important questions remain about how deleterious genetic changes may occur in cultured populations. Are genetic changes produced by low founder sizes (i.e., too few individuals contributing genes to the population) inadvertent domestication, variable family survival rates, by a combination of these elements or by other factors? Can management strategies be implemented to reduce the likelihood of genetic changes when fish are placed into hatcheries? Additionally, once genetic changes occur, what impact do they have on the fitness of natural populations that interbreed with hatchery fish? Studies within the Basin have examined how spawning fitness in natural populations of steelhead and spring Chinook has changed due to supplementation, and more studies are underway. Results from these investigations have improved our knowledge of how supplementation programs impact natural populations. Another component of this uncertainty is an assessment of the efficacy of the management guidelines that regulate (1) the proportion of hatchery fish allowed to spawn in nature and (2) the proportion of hatchery fish used as broodstock. These management guidelines are based on evolutionary theory and are logical. Additional empirical assessments, however, are needed to verify assumed effects. This critical uncertainty is from the 2006 Research Plan; see Part 2, CU #4, for a discussion of progress made toward addressing this uncertainty.

Harvest

1. What is the spawning escapement or harvest rate (range), accounting for hatchery and natural fish and nutrient return, needed to sustain productive fish populations and fish harvests in the future? What is the biological goal for spawning escapement?

This knowledge is needed to understand if escapements are sufficient to achieve the Fish and Wildlife Program's Appendix D Goal 13: "Achieve full mitigation for anadromous fish, native resident fish, and wildlife losses by restoring healthy, self-sustaining, and harvestable, natural-origin anadromous fish….and resident fish." A biologically based spawning escapement goal is the number of spawners required to potentially maximize the average harvest or return for a specific population in the foreseeable future. Knowledge and application of biologically based spawning escapement goals are fundamental to sound harvest and hatchery management. Where possible, biological escapement goals should be based on stock recruitment curves (i.e., the relationship between parent spawning escapement and the abundance of their progeny).

These goals, which consider productivity and carrying capacity of the population (See Programmatic Comment 6; ISAB 2015-1), can be used to evaluate effects of harvests on fish populations (or stock management units) and to identify when observed spawning escapements are too low, adequate, or too high. The biological goals should also consider (1) pHOS guidelines developed by the Hatchery Scientific Review Group (HSRG) and (2) if spawner abundances in excess of carrying capacity are needed to support ecosystem function. Some biologically based goals already exist in the Basin, but many more could be developed.

2. What new harvest and escapement strategies (including selective harvest) can be employed to improve harvest opportunities and ecological benefits within the Columbia River Basin while minimizing negative effects on ESUs (evolutionarily significant units) or populations of concern?

This question is fundamental to Fish and Wildlife Program's Appendix D Goal 18: "Enhance harvest of anadromous fish….." and the legal requirement to mitigate for lost fishing opportunities. Harvesting surplus hatchery fish could benefit both people and natural origin populations; opportunities to do so exist when the total spawning escapement exceeds carrying capacity. Some strategies exist for targeting surplus hatchery fish, but further development is needed to address challenges such as catch and release mortality and opposition to marking fish visually and releasing fish that have been captured. Concerns that efficient use of surplus hatchery fish might lead to reduced efforts to restore habitat and improve production of natural populations must be addressed. This critical uncertainty is from the 2006 Research Plan; see Part 2, CU #25, for a discussion of progress made toward addressing this uncertainty.

Example sub-uncertainty:

2.1. What is the catch-and-release mortality by species and stock, and in relation to environmental variables in the ocean, estuary and freshwater?

3. How can fishery interceptions and harvests of ESUs or populations, both hatchery and wild, best be managed to minimize the effects of harvest on the abundance, productivity, and viability of those ESUs and populations?

Most fisheries in the ocean and in the Columbia River mainstem harvest salmonids from a variety of populations and hatcheries. Better information is needed on the stock composition of fish in mixed-stock fisheries both within and outside the Basin to manage and evaluate harvest impacts on natural-origin populations. Newly emerging tools could improve the accuracy and the cost effectiveness of stock identification. The information can be used adaptively by managers to achieve harvest rates (range) needed to sustain productive fish populations and fish harvests in the future (see Biological Goal above for identification of sustainable harvest rates). This critical uncertainty is derived from the 2006 Research Plan; see Part 2, CU #24, for a discussion of progress made toward addressing this uncertainty.

Example sub-uncertainties:

3.1. Are hatchery harvest rates a reasonable surrogate for wild salmon harvest rates in freshwater and the ocean?

3.2. What are the impacts of directed (intentional) and incidental (unintentional) harvests on population-specific characteristics and productivity of Columbia River Basin fishes?

Population structure and diversity

1. What factors within and outside of the Columbia River Basin influence trends in recruitment, mortality, and abundance of Columbia River Basin fish and wildlife populations?

Understanding how environmental and ecological factors affect vital rates and abundance of fish and wildlife populations in the Basin is critical for guiding management actions to improve population status. The uncertainty varies widely among species and is typically greatest for factors affecting migratory fish and wildlife during life stages spent outside the Basin. However, the ocean synthesis has provided considerable information on how salmon growth and abundance are influenced by food availability and other factors (Jacobson et al. 2012). The list of potential factors is long, and six more specific sub-uncertainties were each given high criticality ratings.

Example sub-uncertainties:

1.1. What are the relative contributions of habitat loss, harvest, predation and mainstem passage to reduced riverine survival and production of anadromous salmonids and other fishes targeted in the Fish and Wildlife Program?

1.2. After anticipated restoration of tributary habitats and given the range in ocean conditions and spawner densities, what level of SARs is needed for each salmon ESU in order to (1) provide for a self-sustaining population, and (2) provide harvests that meet harvest goals?

2. What is the current range of biological diversity (life history and genetic) of fish and wildlife populations in Columbia River Basin ecosystems, and how is that diversity in focal populations influenced by geographic location and changing environmental conditions?

This uncertainty reflects inadequate knowledge about existing biological diversity and its role in maintaining viable populations of fish and wildlife in the Basin. Human actions, including fisheries have reduced the range of life history strategies and genetic diversity in many native fish populations. Although the scope of the uncertainty is long-term and basinwide, efforts to monitor trends in diversity are needed to help understand factors responsible for changes in diversity and to guide management actions to restore habitat loss and mitigate the impacts of *climate change. Maintaining diversity is considered essential to long-term sustainability, as described in the scientific principles that guide the Program.*

Genetic differences arising from geographical isolation among salmonid populations are well documented (e.g., Project # 2009-005-00 "Influence of environment and landscape on salmonid genetics"), but our understanding of the long-term consequences of these differences for ecological and evolutionary performance is more theoretical. Patterns of genetic diversity in widely distributed species, like cutthroat trout, offer an opportunity to assess where historical watershed connections may have existed and can help to explain the current distribution of biological diversity across a landscape (e.g., Loxterman and Keeley 2012).

3. What life history strategies are utilized by Columbia River Basin fishes (e.g., Pacific salmon, lamprey, sturgeon, eulachon), and how do they influence survival and growth in tributaries, the mainstem above and below the dams, estuary, and ocean plume?

Greater understanding of the life history diversity of focal species is needed to set appropriate targets for abundance, distribution, and harvest rate and to improve strategies for habitat restoration and hatchery supplementation. Potential benefits of improved management are large and long-term because life history diversity enhances the basinwide carrying capacity of the species as well as its adaptability to environmental changes in the future.

4. How do fish move among rearing habitats, and what is the importance of habitat connectivity and spatial distribution?

This uncertainty has long-term and basinwide implications for the effectiveness of habitat restoration projects that are central to the Program. Understanding how fish move among habitats and how much connectivity is needed to maintain the viability of focal populations can also guide landscape planning decisions that affect the spatial distribution of efforts to restore habitat or mitigate for climate change. Knowledge varies among species and regions. Some aspects of this uncertainty may need to be resolved at relatively small scales to understand how projects interact and could complement one another. Kanno et al.'s (2014) study of brook trout movements inferred from PIT tag detections and genetic pedigree data could serve as a template for future research.

5. What is the relationship between genetic diversity and ecological and evolutionary performance, and to what extent does the loss of stock diversity reduce the fitness, and hence survival rate and resilience, of remaining populations?

Recognition that genetic diversity is critical to long-term ecological and evolutionary performance is fundamental to the landscape approach and the 2014 Program. Research and adaptive management to address this uncertainty could have long-term, basinwide benefits by identifying and averting management actions that would jeopardize genetic diversity and the resilience of focal populations. Our understanding of the long-term consequences of genetic diversity for ecological and evolutionary performance is still primarily theoretical (e.g., Fraser

2008) and more empirical research is needed. This critical uncertainty is from the 2006 Research Plan; see Part 2, CU #29, for a discussion of progress made toward addressing this uncertainty.

6. How effective is genetic assessment for determining trends in population status and population diversity?

The capability to track trends in abundance, harvest rates, and straying in steelhead and Chinook has increased dramatically with the development of Parentage Based Tagging (PBT) and Genetic Stock Identification (GSI) methods based on SNP (single nucleotide polymorphism) panels. Further technical development of SNPs and PBT looks feasible. Already these genetic assessment tools appear to hold much promise for cost-effectively monitoring trends in population status and population diversity in salmon and other species. The Pacific Salmon Commission is currently considering the use of PBT and GSI.

7. How can the abundance and diversity of salmonid populations in the Columbia River be increased and sustained over the long term given the multitude of biological, physical, and cultural constraints? In particular, what are the potential benefits and risks of re-introducing anadromous fish into blocked areas throughout the Pacific Northwest?

This uncertainty is central to the vision and goals of the Program and focuses on practical strategies that are consistent with a landscape approach needed for improving current Program activities. Current knowledge is low, potential benefits are large, and research seems feasible. Much remains to be learned about how hatcheries and environmental changes will affect the long-term sustainability of natural salmon populations. A number of projects within the Basin are examining the effects of supplementation on natural population abundance and productivity. Climate change is expected to alter the distributions of salmonids, especially bull trout and cutthroat trout, and continued monitoring and evaluation will be required. Efforts to re-introduce anadromous salmonids to blocked areas with favorable water flows and temperatures (e.g., to higher elevations or more northerly locations) may prove beneficial to the long-term viability of salmon populations in the Basin. However, specific uncertainties about the effectiveness and unintended consequences of re-introduction remain to be addressed.

Example sub-uncertainties:

7.1. What is the success rate of the current efforts at re-introducing anadromous fish into locked areas throughout the Pacific Northwest?

7.2. Can extirpated populations be recolonized by relying on out-of-basin brood stock?

8. What is the abundance, distribution and diversity of Pacific lamprey in the Columbia River Basin?

This uncertainty is deemed critical because of serious concerns about the current abundance of Pacific lamprey in the Basin. It will be especially important to identify and protect diversity in

Pacific lamprey in tandem with artificial propagation efforts. Research to address the uncertainty seems feasible with large potential benefits for improving management strategies and recovering the species.

Considerable knowledge already exists about the general life history of Pacific lamprey, including adult migration, overwintering, attraction to pheromones, fecundity, early development, emergence and initial settlement as ammocoetes, sediment preferences, and factors affecting growth. However, more information is needed about trends in the abundance and distribution of both juvenile and adults, about the current population structure and range of life history diversity, and about population dynamics and factors affecting productivity and carrying capacity. This general uncertainty encompasses six other uncertainties about more specific aspects of lamprey ecology and management.

Example sub-uncertainties:

8.1. What are mortality rates for lamprey by life-stage?

8.2. What are the levels of genetic diversity and degree of spatial genetic differentiation among populations or aggregations of Pacific lamprey from the Columbia River Basin and rivers along the west coast of North America? Specifically, what are the genetics of anadromous and resident lamprey populations (e.g., existence of genetically distinct population structure, rate of gene flow, population/subpopulation characteristic, etc.)?

9. What is the status of white sturgeon populations in the Columbia River Basin?

This uncertainty is deemed critical because of serious concerns about inadequate recruitment and connectivity for white sturgeon populations above Bonneville Dam. Considerable research on factors affecting recruitment is underway for some populations, and it is essential that these efforts continue. Connectivity is a concern for all migratory species in the Basin and is likely a critical issue for the long-term viability of white sturgeon. Parent Based Tagging and other genetic methods appear well suited to addressing this uncertainty, particularly given the prominent role of artificial propagation in maintaining the abundance of landlocked populations of white sturgeon. Further development of such technical capacity seems feasible and may be of value in measuring connectivity and maintaining genetic diversity. This general uncertainty encompasses 11 other more specific uncertainties related to white sturgeon.

Example Sub-uncertainties:

9.1. What factors are limiting recruitment of white sturgeon above and below Bonneville Dam?

9.2. Do the mainstem dams isolate sturgeon populations, and if so, what is the feasibility of restoring connectivity to maintain genetic diversity in the long-term?

Monitoring and evaluation methods

1. Fish survival is currently estimated using capture-recapture methods. How can advances in genetic stock identification, reductions in sizes of tags, new tag technologies, and other emerging methods be used to improve estimates of survival (better precision and less bias) and/or reduce costs?

Fish survival is one of the primary metrics of performance. Better estimates will allow more reliable detection of finer differences in survival rates among stocks, under different hydrosystem operations, or for different life stages thereby providing opportunities to develop management actions to help stocks with low productivity. Monitoring and evaluation of fish population status is a critical task that should occur every year as a means to inform decisions involving harvests, hatchery production, and efforts to restore fish populations (See Programmatic Comment 7). Some fish monitoring, including tagging, is funded by the Program, but much of it is conducted outside the Program by government agencies. A common strategy by the Program and outside agencies, along with cooperation and integration of efforts, is needed to effectively and efficiently achieve the goals for monitoring and evaluation in the Basin.

A limitation of tagging methods is the requirement to physically handle fish and apply tags. If handling fish or the physical tag affects subsequent behavior (including survival), estimates of performance may be biased. Tagging methods also require substantial numbers of fish to be tagged to compensate for subsequent mortality and imperfect detection—this may be costly and logistically difficult to do and may not be feasible for species with low abundance. Parent-based genetic tagging appears promising based on the pace of development to date. Smaller and injectable acoustic tags would make it possible to tag smaller juvenile salmon and also juvenile lamprey to assess survival over dams. The increased use and establishment of PIT tag arrays in subbasins would provide information on straying and spawning.

Example sub-uncertainties:

1.1. What are the acute and chronic effects of various tag types on fish survival, for example PIT-tag effects on juvenile salmonids?

1.2. Can survival of juvenile salmonids from spawning to estuary be best monitored using PIT tags, acoustic tags, genetic or other tags?

1.3. What methods can be used to estimate the survival and abundance of lamprey?

Programmatic Comment 7. Brood tables

Ideally, for anadromous salmonids, a monitoring goal should be to develop "brood tables" for each population or stock management group and to use these tables to evaluate stock status (ISAB 2015-1). A brood table shows the annual abundance of the parent spawning population (escapement from the fishery) and the number and sex of returning progeny at each age class. To obtain this information, adult salmon returning annually must be enumerated by age (e.g., with scales or otoliths) and then assigned to the proper parent spawning year (i.e., brood year). Fish captured in ocean and mainstem river fisheries originate from multiple populations; therefore, an important task is to identify the population (stock) composition of fishery harvests so that the fish can be assigned to the proper brood table. The number of hatchery and natural origin spawners must be enumerated separately to maintain accurate statistics for the determination of natural population. Otherwise, stock status may be confounded by the presence of hatchery salmon. Monitoring of smolt production by size and age is important for identifying changes in recruitment associated with the spawner-to-smolt stage versus the smolt-to-adult stage. With very few exceptions, a complete enumeration is too costly and logistically impossible. Consequently, a well-designed random sample with appropriate expansion factors is required to obtain unbiased estimates of the brood table.

Brood tables are fundamental for developing recruitment curves, which can then be used to determine intrinsic productivity and the maximum equilibrium abundance (population carrying capacity) in the existing habitat. This information is vital for harvest management and for evaluating fish responses to habitat restoration and supplementation efforts.

While brood tables are important summary measures of population status, more detailed and refined estimates at earlier life stages are needed to evaluate habitat actions and identify where density dependence is limiting recovery. For example, to evaluate the success of a habitat restoration activity, fish-in (spawning adults) and fish-out (smolts) estimates are needed for that specific segment where habitat restoration took place. Again a complete enumeration is often not feasible and so a well-designed sampling plan is needed.

Data from monitoring and evaluation, including historical datasets, should be maintained in online databases so that interested parties have access to the data. Many data are stored at websites such as StreamNet, the Fish Passage Center, the Pacific Fishery Management Council, NOAA salmon population summary, and the Northwest Power and Conservation Council. Some long-term datasets, such as those reported by Columbia River Fish Runs (84 data tables) need to be made more accessible than they are at present. Because the large natural variability in population numbers is often caused by factors that cannot be controlled (e.g. weather and climate), long term data sets are necessary to evaluate the success and robustness of programs to restore salmon under many different external regimes. Before terminating a data series, careful consideration is needed to determine whether or not this termination is premature.

2. Are there effective methods for fish-in and fish-out monitoring for measuring effects of habitat restoration and other changes?

Ideally the number of fish entering a restored habitat (fish-in, e.g. spawning adults for spawning habitat restoration; juvenile fish for rearing habitat restoration) and the number of fish leaving a restored habitat (fish-out, e.g. juveniles produced or juvenile fish moving to other habitats) can be enumerated. The difficulty is that the habitat areas often cannot be closed off and fish are difficult to detect. Costly methods (e.g., fences and rotary screw traps) are often used, but these methods are not suited for high water conditions when fish are actively moving. Resolving this uncertainty will lead to more rapid learning and propagation of effective restoration actions to other parts of the Basin. Reducing uncertainties in fish-in and fish-out monitoring by reducing bias and increasing precision could lead to better evaluation of the effects of habitat restoration for all species of fish.

Example sub-uncertainties:

2.1. How do we best estimate the number of juvenile-recruits per spawner given tradeoffs between costs, precision, and accuracy?

2.2. What statistical methodologies are available for estimating the number of fish (1) entering and then leaving habitat areas or for (2) entering and the number of progeny leaving the habitat area? And how effective are the statistical methodologies for different habitat types?

3. What are the most effective methods for quantitative estimates of changes to abundance, survival, movement, and production in response to habitat restoration, and how can these estimates be integrated across a range of spatial scales from individual restoration treatments to whole watersheds, and temporal scales from individual seasons to entire life cycles?

Effective methods are available to quantitatively estimate abundance, survival, movement, production and habitat capacity over reach scales (or between two reaches). However, the methodology for integrating these estimates to assess effects of human activities and restoration across watershed scales and through several generations of fish or wildlife has not been sufficiently studied. Because of these large scales, relatively little is known about whether current methods are accurate. As well, there are many smaller habitat restoration projects implemented, each of which may contribute only a small amount to a stock's overall performance and whose benefits are difficult to detect. By understanding the cumulative effects, the benefit of restoration activities can be quantified to see if they are cost effective compared to other actions.

Example sub-uncertainties:

3.1. Are habitat actions substantially increasing abundance of focal species? Are models used to predict habitat benefits of actions prior to implementing actions accurate and useful in order to prioritize actions and assess cost/benefit ratios?

3.2. Do the current methods for detecting effects of many small, incremental habitat improvements on fish populations provide answers with sufficient precision and accuracy to evaluate the success of these programs?

4. How can the impacts of restoration activities on wildlife populations (other than fish) be effectively monitored?

Wildlife monitoring is a critical component in the landscape-scale approach to assessing ecosystem health. Monitoring of impacts on wildlife populations provide a critical and more enhanced view of the overall effects of restoration actions. Interactions between species (e.g., bears transporting nutrients to forests via salmon) need to be understood to evaluate impacts of management actions. Currently, there is often little systematic monitoring of non-fish species.

Example sub-uncertainties:

4.1. Can impacts to transient wildlife populations (e.g., waterfowl) be effectively monitored?

4.2. Can impacts to small localized wildlife populations (e.g., bears) be effectively monitored?

Part 2. Summary of Progress toward Addressing 2006 Research Plan Critical Uncertainties

Review Process

This part of the report answers the Council's review question to the ISAB and ISRP: "***Is ongoing research making progress in answering critical uncertainties in the current [2006] research plan?"*** Specifically, we evaluated the most recent annual progress reports for 187 ongoing 2015 Fish and Wildlife Program projects that contain a research, monitoring, or evaluation work element[9] to determine the extent to which the projects directly address or could potentially help address the 2006 Research Plan critical uncertainties. We acknowledge that focusing on only the Fish and Wildlife Program projects and recent annual reports gives an incomplete picture of progress made and efforts directed to addressing the uncertainties. Our programmatic comments in the Executive Summary and Appendix D to Part 2 describe some difficulties with using our examination of annual reports to track overall program progress toward addressing critical uncertainties. We did not conduct an extensive literature search on the state of the science for each 2006 critical uncertainty. Instead, we relied on our collective knowledge and familiarity with recent synthesis reports and research efforts outside the Fish and Wildlife Program to inform our answers about progress made on the 2006 questions—for example, the Army Corps of Engineers Anadromous Fish Evaluation Program, the Lower Snake River Compensation Plan, and synthesis reports by ocean, estuary, and sturgeon researchers. Thus, knowledge arising from these outside efforts was captured opportunistically, and our review of progress on the 2006 critical uncertainties should not be considered all encompassing.

In the summaries below, **"Direct"** means that the project directly addresses the 2006 Research Plan critical uncertainty (CU), at least in part, by testing a hypothesis associated with the CU or by generating results that are contributing or will contribute to resolving the CU and to improving Fish and Wildlife management decisions and actions. Most of the studies we reviewed were restricted to particular species or locations whereas the 2006 critical uncertainties typically include multiple species and are basinwide in scope. Consequently, projects were identified as "Direct" even if they addressed only part of an uncertainty as long as information generated by the project was being applied or could help to resolve some aspect of the critical uncertainty. The fact that numerous projects address an uncertainty does not imply that the uncertainty is comprehensively addressed.

"**Indirect or Potential**" means that data gathered by the project is (1) being used by another project to address a critical uncertainty or (2) could potentially address a critical uncertainty, but to be useful, additional analysis, compilation, and synthesis would be required. These "potential" connections highlight opportunities for further data analysis, collaboration, and coordination among projects. They show that data collected through monitoring and evaluation projects may be used to develop and test hypotheses. Notably, some ISAB and ISRP reviewers liberally identified potential connections while

[9] BPA defines a work element as a "standardized task or activity performed by BPA's Fish and Wildlife program. Examples include Install Fence, Collect Data, Purchase Land, and Submit Progress Report."

others were more conservative. Thus, the results should be viewed as a snapshot of opportunities for additional analyses or collaborations to address uncertainties.

Our evaluations of “**Progress”** are only approximate because they are based primarily on information contained in annual reports and limited by our familiarity with the literature connected to each uncertainty. Refining our evaluation of progress will require a thorough literature review of each theme that is beyond the scope of our review. However, in the interim, we hope that additional contributors to the Council’s Research Plan will improve our initial assessments by considering results from any pertinent studies we overlooked that occurred within or outside of the Basin.

Fish Propagation

Table 1. The fish propagation theme[10] uncertainties in the 2006 Research Plan and the number of Fish and Wildlife Program projects that directly or potentially addressed each one.

ID	2006 Research Plan Critical Uncertainty (select to see specific projects)	Directly	Potential
1	What is the cost to natural populations from competition, predation (direct and indirect), and disease caused by interactions with hatchery-origin juveniles and from harvest in fisheries targeting hatchery-origin adults?	5	8
2	To what extent can interactions between production-hatchery fish and naturally produced wild fish be reduced — for example with the goal of achieving sustainable long-term productivity and resilience of the wild component of the population by spatial or temporal partitioning of natural and artificial production at the subbasin, province, basin, and regional scale?	15	10
3	What is the magnitude of any demographic benefit to the production of natural-origin juveniles and adults from the natural spawning of hatchery-origin supplementation adults?	20	18
4	What are the range, magnitude, and rates of change of natural spawning fitness of integrated (supplemented) populations, and how are these related to management rules, including the proportion of hatchery fish permitted on the spawning grounds, the broodstock mining rate, and the proportion of natural origin adults in the hatchery broodstock?	13	16
5	Can the carrying capacity of freshwater habitat be accurately determined and, if so, how should this information be used to establish the goals and limitations of supplementation programs within subbasins?	11	12
6	What is the relationship between basinwide hatchery production and the survival and growth of naturally produced fish in freshwater, estuarine, and ocean habitats?	0	19
7	What effect do hatchery fish have on other species in the freshwater and estuarine habitats where they are released?	5	14

Summary

If answered, the seven artificial propagation uncertainties in the 2006 Research Plan would help identify the benefits and the unintended consequences of the hatchery programs now occurring in the Basin. Four of the uncertainties focus on interactions between hatchery juveniles and the natural fish they encounter as they move through freshwater and marine habitats. These uncertainties are directed toward: (a) discovering the magnitude of potential competitive and predaceous interactions and

[10] For further background on this theme see the 2006 Research Plan summary (pages 11-12) and the Fish and Wildlife Program strategy on fish propagation including hatchery programs.

pathogen transfers between hatchery and natural fish, (b) determining whether hatchery programs can be developed to limit possible interactions between hatchery fish and natural-origin fish, and (c) assessing the cumulative effects of annual releases of hatchery salmonids on the survival of natural fish in the Basin's freshwater and estuary habitats as well as ocean feeding grounds.

The remaining three uncertainties are concerned with how conservation, supplementation, and integrated hatchery programs: (a) affect the abundance and productivity of the natural populations they were designed to augment, (b) influence the fitness of fish spawning in nature, and (c) respond to carrying capacity issues in the habitats where the fish will be released. Even though progress has been made on understanding the effects of the Basin's hatchery programs since the establishment of the 2006 Research Plan, much remains unknown. Because this information is essential for achieving the goals of the Fish and Wildlife Program, the artificial propagation uncertainties presented in the 2006 Research Plan are as relevant today as when they were first proposed.

2006 Critical Uncertainty 1: What is the cost to natural populations from competition, predation (direct and indirect), and disease caused by interactions with hatchery-origin juveniles and from harvest in fisheries targeting hatchery-origin adults?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #1.

A. Progress and Criticality

Progress–High: Information on how salmonid hatchery production affects the abundance and biomass of native fish populations has been collected and analyzed in a number of subbasins. Less effort has been focused on whether hatchery fish act as pathogen vectors to natural-origin fish but a study designed to look at pathogen transfer was conducted in the Yakima subbasin (Fast et al. 2015). Additionally, the impacts on natural-origin fish from a few fisheries targeting hatchery salmonids have been evaluated (Kostow 2011, Ann. Proj Rept. 1993-060-00). Parentage Based Tagging[11] (PBT) and genetic stock identification (GSI) methods that rely on single nucleotide polymorphisms (SNPs) have been recently developed (Ann. Proj. Rept. 2008-907-00). These genetic tools have been used to identify the origins of harvested hatchery and wild fish and will be used in the future to investigate the effects of fisheries on natural-origin fish.

Criticality–High: Although progress has been made on addressing this uncertainty, further information on the competitive and predaceous interactions between hatchery- and natural-origin fish is needed in

[11] Parentage Based Tagging is a genetically based fish marking method that occurs at fertilization. DNA samples are collected from all the fish used as broodstock at a hatchery. Genetic profiles based on single nucleotide polymorphism (SNP) panels are used in pedigree analyses to determine if a sampled fish can be matched to particular hatchery parents. If a sampled fish is of hatchery origin, its parents, age, and the hatchery it originated from can be identified. Once its parents are known it may also be possible to identify its rearing treatment and release date.

subbasin, mainstem, estuary, and ocean plume habitats to ascertain if changes in hatchery release times or abundance levels are needed to protect weakened natural populations.

B. Contributions from Fish and Wildlife Program Projects

Several studies in the Basin have examined competitive, predaceous, and disease effects of hatchery fish on natural-origin fish. Possible disease transmission from hatchery fish to natural-origin fish, for instance, was examined in the Yakima Subbasin where a spring Chinook supplementation program is taking place. No increase in disease causing organisms was detected (Fast et al. 2015). Additionally, protocols developed by Pearsons and colleagues are being used to evaluate competitive and predaceous interactions between juvenile hatchery spring Chinook and natural-origin fishes in the Yakima subbasin (Pearsons et al. 1998, Pearsons and Hopley 1999, Ham and Pearsons 2001). Similar efforts to evaluate possible effects of hatchery fish on natural fish are taking place in the Clearwater, Wenatchee, Methow, and Salmon subbasins**.** Deleterious interactions between hatchery- and natural-origin fish in these subbasins appear to be low (Galbreath et al. 2014, Fast et al. 2015).

Interactions between juvenile hatchery- and natural-origin fish also occur in the mainstem and lower portions of the Columbia River and have not been studied as intensively as those that take place in subbasin areas, but they could be quite important. Releases of hatchery fall Chinook into the Snake River, for example, caused earlier dispersal of natural parr from the Lower Granite Reservoir and reduced parr growth rates and size at emigration. Additionally, smallmouth bass abundance and predation on juvenile salmonids increased in the reservoir as the fall Chinook hatchery program expanded (Ann. Proj. Rept. 1991-029-00).

Ecological interactions between juvenile hatchery and wild fish in the estuary and ocean plume have also been assessed. Significant progress has been achieved in identifying when specific groups of hatchery and wild salmonids arrive in the estuary, ocean plume, and what portions of nearshore habitat they typically occupy. Hypotheses about how hatchery fish may impact growth and survival of natural-origin salmonids in these habitats are being examined (Ann. Proj. Rept. 1998-01-400).

The Select Area Fishery Enhancement (SAFE) program is one of the few projects in the Basin that is investigating how fisheries targeting hatchery adults may affect natural-origin salmonids. Fishing effort is concentrated in areas where natural-origin fish are not expected to occur. Consequently, impacts to natural-origin populations have been minimal and further reductions have occurred because managers have continued to make refinements to the SAFE program (Kostow 2011, Ann. Proj. Rept. 1993-060-00). The Colville Tribe's selective fishery program (Ann. Proj. Rept. 2003-023-00) is also designed to harvest hatchery fish in a location not frequented by natural-origin adults (i.e., adjacent to the Chief Joseph Hatchery).

Additional assessments of harvest impacts on natural stocks will depend, in part, on the ability to identify the origin of harvested fish. The advent of single-nucleotide polymorphism (SNP) panels has made it possible to use Parent-Based Tagging (PBT) to identify the parental origins of hatchery fish. SNP panels have also been used to improve genetic stock identification (GSI) methods allowing for finer identification of natural-origin stocks of salmonids (Ann. Proj. Rept. 2008-907-00). Use of PBT is expected to increase in the future and further identification of SNP variation in natural populations is occurring. Similarly, SNP panels are making it possible for researchers to identify Columbia Basin salmonids in harvests and in the natural habitats they occupy at all stages of their life cycle. Thus, this genetic tool along with routine sampling of harvested fish could improve estimates of harvest rates of natural-origin Columbia River salmonids in ocean and in-river fisheries that are currently based on coded-wire-tagged hatchery salmon.

Assessments of ecological interactions between hatchery and wild fish need to occur in additional subbasins and mainstem reservoirs. Chinook and steelhead have been the primary species studied although some information on coho and sockeye has also been reported. Artificial propagation of white sturgeon and burbot is occurring in the Basin (Ann. Proj. Repts. 1988-064-00, 1988-065-00) and hatcheries may be used to propagate Pacific lamprey in the future. Studies are needed to examine the effects of fish produced from these hatchery programs on native biota.

It is not clear how information from these studies may be used by managers to adjust supplementation or other hatchery programs, or to enable harvests of surplus hatchery fish in terminal areas. These adjustments are policy issues because salmonid hatchery production goals are often set by treaties and mitigation obligations. Thus, changes will have to be negotiated among Basin co-managers.

C. Additional Information

Research on the distribution, arrival timing, and diets of juvenile hatchery- and natural-origin salmonids is being conducted by NOAA and its research collaborators in the Columbia River estuary and adjacent ocean plume (see Estuary and Ocean Sections). Hatchery and wild fish currently have similar arrival timing and diet overlap is high. The potential for competition and behavioral impacts on wild salmonids is great due to the larger size and abundance of hatchery fish (Weitkamp et al. 2015). Additionally, effects of hatchery releases on food webs in the estuary remain largely unknown.

It is well known that hatchery stocks can sustain higher harvest rates than wild salmon populations because fewer broodstock are needed. Harvest managers must take this into consideration when harvesting hatchery salmon. The fundamental question is: how can hatchery salmon be harvested while simultaneously minimizing impacts to co-mingling wild salmon on fishing grounds? Harvest of surplus hatchery fish from segregated hatchery programs is particularly important because fish produced by these programs probably originated from ancestors that were exposed to hatchery conditions for many generations. Thus, these fish are likely well-adapted to hatchery environments, but they and any offspring they produce may be poorly equipped to thrive under natural conditions (*see* Harvest Section).

2006 Critical Uncertainty 2: To what extent can interactions between production-hatchery fish and naturally produced wild fish be reduced — for example with the goal of achieving sustainable long-term productivity and resilience of the wild component of the population by spatial or temporal partitioning of natural and artificial production at the subbasin, province, basin, and regional scale?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #2.

A. Progress and Criticality

Progress–High: The potential consequences of interactions between hatchery salmonids and natural-origin fishes have been the focus of fisheries management in the Pacific Northwest for many years (Fresh 1997, Kostow 2009, Rand et al. 2012). Management practices and hatchery operations have lessened the negative effects of interactions between hatchery salmonids and naturally produced fish at specific points in their life cycles, especially for upriver Chinook and steelhead populations (*see* ISRP 2013-3 for a review). Yet, research, particularly in mainstem, estuary, ocean plume, and nearshore habitats is needed to further elucidate the nature and magnitude of interactions between hatchery and natural-origin fish in these habitats.

Criticality–Medium: Criticality was judged to be medium due to the progress made in developing management approaches that can mitigate the impacts of hatchery fish on wild fish. However, the preponderance of hatchery salmonids in the Basin – and the potential for deleterious interactions with naturally produced fish in the mainstem, estuary, and ocean – still remains a concern.

B. Contributions from Fish and Wildlife Program Projects

Several types of research have been used to assess how interactions between hatchery salmonids and naturally produced fish could be reduced. Some has been directed toward discovering whether artificial culture has genetically and phenotypically altered cultured salmonids (Naish et al. 2008, Christie et al. 2014, Ann. Proj. Repts. 2003-039-00, 2003-054-00, 2003-063-00). Another research aspect identified the impacts that releases of hatchery salmonids may have on natural-origin fish during juvenile and adult life history stages. Results of this work were used to develop management strategies and hatchery practices that could be used to reduce interactions between hatchery- and natural-origin fish (Ann. Proj. Repts. 1993-056-00, 2002-031-00, 2003-039-00, 2009-001-00).

Fisheries managers and researchers recognized that the number of hatchery origin adults allowed on spawning grounds should be controlled to protect the genetic composition of natural populations (Mobrand et al. 2005). Two approaches to regulate hatchery fish abundance on spawning grounds were developed. One relied on the use of purse seines, beach seines, and weirs to harvest surplus hatchery fish and release wild conspecifics. Non-lethal capture of adult salmon appears to be an effective way to limit the abundance of hatchery adults in natural spawning areas (Ann. Proj. Rept. 2008-105-00). However, the survival and reproductive success of natural fish captured by these methods and released to spawn has not been evaluated and remains an important need. The other approach, used by the SAFE program and Chief Joseph Hatchery, spatially separates hatchery adults from natural-origin fish. In the SAFE program, hatchery juveniles are reared in net pens in areas with few natural-origin fish. At the adult stage, the fish home to their net pen locations where they are subjected to commercial fishing with harvest rates close to 100% (Ann. Proj. Rept. 1993-060-00). Similarly, hatchery adults produced from the Chief Joseph Hatchery will be harvested in an area adjacent to the hatchery where few natural fish are expected to occur (Ann. Proj. Rept. 2003-023-00). These approaches, however, currently apply to just a small fraction of the Basin's hatchery populations.

Hatchery strays may alter the genetic composition and subsequent productivity of natural populations and can be a serious problem (Keefer and Caudill 2012, ISRP 2013-3). A series of studies on the use and operation of acclimation ponds took place to see if they could be utilized to reduce straying. These studies showed that volitional releases of fish from acclimation sites located in prime rearing and spawning locations substantially reduced straying (*see* ISRP 2013-3 for a review, Ann. Proj. Rept. 2007-299-00). Ancillary work disclosed that adults that had been transported downstream in barges at the smolt stage often failed to return to their natal streams and that straying could be further reduced if transportation was curtailed (Ann. Proj. Rept. 2007-299-00). The origin of a hatchery's broodstock also has been found to affect straying rates. This knowledge led to the development of broodstocks using local natural-origin fish which helped decrease the occurrence of strays (*see* ISRP 2013-3).

Conditions in some salmonid hatcheries accelerate maturity in male salmonids. In spring Chinook hatcheries, for example, more than 50% of the males in a brood may reach maturation at age 1+ and become minijacks (Larsen et al. 2004). Once released, minijacks may remain in the subbasin where they were released, migrate to a mainstem reservoir, or travel downstream to the estuary prior to returning to freshwater spawning grounds at age 2 (Beckman and Larsen 2005, Johnson et al. 2012). While in these habitats, they likely compete with and possibly prey on native fishes. Precocious maturation was found to be influenced by diet, broodstock source, and when fish were first fed. Diet formulations, feeding guidelines, and the use of water chilling equipment to control incubation rates have been used successfully to reduce rates of precocious development in Chinook (Larsen et al. 2006, Ann. Proj. Rept. 2002-031-00). Hatchery steelhead may also exhibit early maturation; these fish called residuals do not migrate to the sea. Instead residuals may compete with or prey upon native fishes and spawn with resident rainbow trout and anadromous steelhead. Research conducted in the Basin has shown that their presence in streams may be controlled if hatchery steelhead are volitionally released from rearing sites (*see* ISRP 2013-3 for a review). Typically, steelhead destined to become residuals will remain in a raceway, even when provided with an opportunity to leave, and thus can be collected at the end of a release period.

Hatcheries for white sturgeon are in operation in the Basin and more may be developed (Ann. Proj. Rep 1988-064-00). Additionally, releases of hatchery burbot (Ann. Proj. Rept. 1988-065-00) have recently occurred and releases of hatchery-reared Pacific lamprey may occur in the future (Ann. Proj. Rept. 2008-470-00). The possible impacts of these programs will need to be evaluated to determine whether management changes are needed to protect natural biota. Knowledge for this uncertainty for non-salmonids (e.g., white sturgeon and Pacific lamprey) needs to be developed.

2006 Critical Uncertainty 3: What is the magnitude of any demographic benefit to the production of natural-origin juveniles and adults from the natural spawning of hatchery-origin supplementation12 adults?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #3.

A. Progress and Criticality

Progress–Medium: A number of studies in the Basin have examined whether an increase in natural salmonid abundance occurs after hatchery fish are allowed to spawn under natural conditions (Scheuerell et al. 2015, Ann. Proj. Repts. 1983-350-03, 1995-063-25, 1998-007-02, 2008-710-00). Numerous factors, including the target species, project location, broodstock history, where fish are released, age and size of the naturally spawning hatchery adults, habitat carrying capacity, and the genetic diversity of hatchery fish, have been linked to how supplementation affects the abundance of natural-origin fish (Hoffnagle et al. 2008, Williamson et al. 2010, Ann. Proj. Repts. 1989-096-00, 1990-005-00, 2003-028-00, 2009-001-00).

Criticality–Priority: The long-term demographic benefits of most of these programs, however, are still under evaluation. Thus, significant questions remain about the magnitude of potential benefits (and risks) of supplementation using an integrated hatchery approach.

B. Contributions from Fish and Wildlife Program Projects

Three types of fish culture strategies have been used to increase abundance of natural-origin salmonids: (1) captive brood programs, (2) reintroductions using hatchery stocks, and (3) supplementation efforts. Captive brood programs for spring Chinook in the Salmon and Grande Ronde rivers (Ann. Proj. Repts. 2007-083-00, 2007-403-00) and sockeye in the Snake River (Ann. Proj. Rept. 2007-402-00) have rescued severely depressed populations from extinction. Adults produced from those programs have successfully spawned in nature and produced adult offspring. Abundance has increased to the point where the spring Chinook captive brood programs are no longer needed. The status of Snake River sockeye continues to improve. Out-of-subbasin hatchery stocks are being used to reintroduce species of salmonids into parts of the Basin where they had been extirpated (Ann. Proj. Rept. 1996-040-00, 2000-

[12] Two types of hatchery programs are possible, integrated and segregated. “A hatchery program is an *Integrated Type* if the intent is for the natural environment to drive the adaptation and fitness of a composite population of fish that spawns both in a hatchery and in the wild” (HSRG, WDFW, NWIFC. 2004a). “A hatchery program is a *Segregated Type* if the intent is for the hatchery population to represent a distinct population that is reproductively isolated from naturally-spawning populations” (HSRG, WDFW, NWIFC. 2004b). Integrated programs incorporate natural-origin adults into their broodstocks (up to 100%) while segregated programs primarily use hatchery-origin adults. Supplementation is an example of an integrated hatchery program. It can be a short-term conservation effort that ceases after population abundance has reached a pre-established goal. It can also be a long-term effort meant to produce fish that will be allowed to spawn in nature as well as contribute to fisheries.

039-00, 2008-710-00, 2009-009-00). For example, reintroductions are taking place for coho in the Wenatchee, Methow, Clearwater, and Yakima rivers; chum salmon into the Chinook River, Big Creek, and Duncan Creek; sockeye in Cle Elum Lake; and spring Chinook into the Walla Walla River, Hood River, and Newsome Creek. Coho are now returning and spawning in the rivers where they were reintroduced and are establishing natural populations. Spring Chinook appear to have re-established themselves in the Walla Walla River, Hood River, and Newsome Creek, and chum salmon have returned and spawned in the Chinook River and Big Creek.

Demographic benefits of supplementation projects have varied substantially. The spring Chinook supplementation program in the Imnaha Subbasin is one of the longest and best studied programs of this type in the Basin (ISRP 2011-14). A recent evaluation found that the total number of fish (hatchery plus wild) returning to the Imnaha Subbasin had increased due to the program. However, examination of adult returns from 28 brood years indicated that natural-origin fish abundance has not increased. Furthermore, since initiation of the program, productivity of natural spawners has decreased.[13] Similar increases in total abundance have been seen among the Yakima River, Johnson Creek, and Lostine River spring Chinook supplementation programs. In the Yakima River, the supplementation program has increased harvests, redd counts, and spatial distribution, but no detectable increase in natural-origin fish has been observed (Fast et al. 2015).

Conversely, a trend of increasing abundance of natural-origin spring Chinook has been noted in the Lostine River over the past four years (Ann. Proj. Rept. 1998-007-02). The fall Chinook supplementation effort in the Snake River has increased overall abundance. Adults produced by this program have been allowed to spawn in nature. Recently, approximately 70% of the fall Chinook spawning in the Snake River subbasin have been hatchery-origin fish. Even though their productivity appears to be low (Recruits/Spawner <1; i.e., not self-sustaining under current conditions), the number of natural-origin fall Chinook returning to the Snake River has increased substantially (Ann. Proj. Rept. 1983-350-03). Increases in overall abundance have also been seen in steelhead supplementation programs. In the Hood River, for instance, hatchery fish doubled the number of fish found on spawning grounds. Yet apparent rapid adaptations to hatchery conditions by Hood River steelhead have significantly reduced their ability to spawn and produce offspring under natural conditions. Thus, no increases in natural steelhead abundance occurred in the Hood River in spite of the large increase in total spawners (Ann. Proj. Rept. 2003-023-00).

The benefits that natural populations may experience from supplementation can be altered by a host of factors. One concern is the surprising ubiquity of density dependence in many threatened populations (Walters et al. 2013, Zabel and Cooney 2013, ISAB 2015-1). In numerous instances, existing habitat conditions cannot support an increase in fish density. Other factors, such as the location of hatchery releases, genetic changes due to inadvertent domestication, and the age and size of hatchery fish allowed to spawn in nature have all been linked to failures of supplementation programs to increase

[13] See http://orafs.org/wp-content/uploads/2015/03/Session-2-5-Hoffnagle.pdf

natural abundance, primarily because these factors negatively affected the productivity of naturally spawning hatchery fish.

Assessing whether supplementation has been responsible for demographic benefits can be difficult. This type of analysis requires pre- and post-project reference streams, infrastructure to sample juveniles and adults, and genetic tools to accurately discern the pedigree history of natural-origin fish. In a number of cases, the lack of reference streams and sampling infrastructure has constrained efforts to evaluate whether supplementation is increasing natural abundance. Studies currently taking place in the Basin, however, will provide more information about the effects of these programs in the future (e.g. Ann. Proj. Rept. 2009-009-00).

Research in the Basin is also addressing issues that are tangential to this uncertainty. For example, the value of incorporating local fish into supplementation broodstocks is being examined in a steelhead project (Ann. Proj. Rept. 2010-057-00). Status and trends data on natural populations in un-supplemented streams are also being collected, and this information may make these streams valuable reference locations when supplementation projects are evaluated in the future (Ann. Proj. Rept. 1997-030-00). Additionally, the effects of habitat restoration on steelhead and spring Chinook abundance are being investigated (Ann. Proj. Rept. 1990-005-01). Potentially, these data could be used by programs to guide habitat restoration efforts in subbasins where supplementation is taking place. Researchers are also investigating how to minimize phenotypic and genotypic differences between hatchery- and natural-origin fish (Ann. Proj. Rept. 2002-031-00). The widespread use of such techniques, if developed, along with habitat restoration actions, could protect natural populations undergoing supplementation and increase the probability of enhancing natural salmon abundance.

C. Additional Information

Most of the research on this uncertainty has occurred within the Columbia River Basin. However, some salmon recovery work in other parts of the Pacific Northwest supports the idea that supplementation can provide substantial demographic benefits to depressed populations if sufficient habitat is available. Supplementation efforts were used to recover ESA-listed summer chum salmon in the Hood Canal-Strait of Juan de Fuca ESU. Natural-origin adults were collected, artificially spawned, and their offspring reared for several weeks prior to being released. These efforts created self-sustaining populations; natural abundance increased from just a few adults to thousands (Kostow 2011). A similar effort occurred in a Strait of Juan de Fuca coho population. Habitat for coho was available, and a supplementation program lasting six years increased natural abundance from less than a hundred adults to over a thousand. This level of abundance has remained even though supplementation stopped over a decade ago (Schroder and Johnson unpubl. data[14]).

[14] See http://svrcd.org/wordpress/wp-content/uploads/2012/02/Johnson%20Snow%20Creek%202-16-12.pdf

2006 Critical Uncertainty 4: What are the range, magnitude, and rates of change of natural spawning fitness of integrated (supplemented) populations, and how are these related to management rules, including the proportion of hatchery fish permitted on the spawning grounds, the broodstock mining rate, and the proportion of natural origin adults in the hatchery broodstock?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #4.

A. Progress and Criticality

Progress–Medium: Answers to five basic questions are needed to assess how spawning fitness in natural populations may change due to supplementation programs. First, does artificial culture cause genetic or phenotypic changes in cultured fish? Second, do those changes reduce the capacity of hatchery fish to reproduce in nature? Third, are those changes carried forward into future generations; that is, are they of genetic origin? Fourth, to what extent will natural selection purge non-adaptive genetic variants when hatchery adults spawn in nature? And fifth, will guidelines associated with hatchery broodstock mining rates (percentage of natural-origin fish in a population used as broodstock), and those that regulate the proportions of hatchery- and natural-origin fish on natural spawning grounds and in hatchery broodstocks, impact the productivity of integrated populations? Answers to questions three through five would help ascertain how different Proportionate Natural Influence (PNI) values or the ratios of hatchery and wild fish on natural spawning grounds and in hatchery broodstocks affect the productivity of natural populations subject to supplementation. Progress has been made in answering questions one through three, but questions four and five still need to be addressed.

Criticality–Priority: Supplementation is a widely used conservation tool; therefore, it is critical to: (a) determine if supplementation lowers the spawning fitness of natural populations where it is being applied, and (b) ascertain whether the guidelines proposed by the Hatchery Scientific Review Group (HSRG) will retain fitness in integrated populations.

B. Contributions from Fish and Wildlife Program Projects

Artificial culture can potentially influence juvenile and adult morphology, physiology, behavior, and genetic diversity in hatchery salmonids and other cultured fishes. Research efforts in the Basin detected a number of differences between hatchery fish and their natural counterparts. Salmonids exposed to traditional hatchery conditions generally matured at younger ages, had decreased sizes at maturation, slightly different body shapes, dissimilar run and spawn timing, sex ratios, fecundity values, and fat content (Knudsen et al. 2006, 2008, Busack et al. 2007, Ann. Proj. Repts. 2003-039-00, 2010-033-00). Many of these differences were likely caused by environmental conditions the fish experienced while being reared in a hatchery. Some differences such as run-timing and behavioral differences in predator avoidance and social dominance were caused by genetic changes (Fritts et al. 2007, Pearsons et al. 2007, Hoffnagle et al. 2008). Molecular methods disclosed additional evidence of genetic differentiation between hatchery- and natural-origin fish. Analyses performed on Hood River steelhead, for instance, revealed that after just two generations, hatchery fish had reduced allelic richness, increases in linkage disequilibrium and relatedness, plus a substantial reduction in effective population size relative to natural-origin steelhead (Christie et al. 2012). These effects on genetic diversity appear to have been caused by a relatively small founder population (40 - 80 fish) and considerable variation in family size.

Conversely, analysis of an integrated hatchery population of upper Yakima River spring Chinook using a genome-wide approach showed little genetic divergence from the source population even after three generations of hatchery exposure (Waters et al. 2015). The PNI values for this population have ranged from 0.57 to 0.83 and averaged 0.64 over the 14 years that supplementation has taken place. Approximately 360 natural-origin fish are used as broodstock each year for this program (no hatchery fish are used in the broodstock). A segregated line at the same hatchery did, however, exhibit genetic drift and temporal signs of adaptive divergence after three generations. The annual broodstock for this line consisted entirely of hatchery fish (~85) produced from the segregated line. These results suggest that initial founder sizes and repeated recycling of fish through a hatchery can create genetic changes in hatchery populations (Waters et al. 2015).

How differences between hatchery and natural-origin steelhead and spring Chinook influence their ability to reproduce in nature has been evaluated in several Basin studies. A recent review by Christie et al. (2014) of these projects indicated that hatchery-origin fish are less successful at producing adult offspring than natural-origin fish. Males are often more adversely affected than females. Factors responsible for this reduction in fitness have been identified and some, such as choice of spawning locations and age and size at spawning, were instigated by environmental conditions experienced in the hatchery or by release location. Others were due to genetic changes caused by hatchery culture. The Hood River steelhead investigations have shown that hatchery adults with one hatchery and natural-origin parent were half as successful at producing adult offspring as hatchery adults derived from two natural adults when the fish spawned in nature. Similar evaluations on the role that parental ancestry may have on the ability of hatchery spring Chinook and coho to produce adult progeny in nature have not revealed this effect (Christie et al. 2014). The Hood River steelhead research program also discovered that naturally produced adults that had two hatchery parents were about 40% as successful at producing adult offspring as those with two wild parents when spawning in nature. This result indicated that genetic changes caused by hatchery conditions can be perpetuated into succeeding generations (Christie et al. 2014). Whether comparable ‘carryover’ effects exist in other integrated populations is not known.

The possibility that hatchery fish spawning in nature could reduce the productivity of supplemented populations prompted the development of a set of management guidelines for salmonids. The HSRG has stated: *“For integrated populations, the proportion of natural-origin adults in the broodstock should exceed pHOS [percentage of hatchery origin adults spawning in nature] by at least a factor of two, corresponding to a PNI value of 0.67 or greater. To reduce ecological risks, the HSRG recommends that census pHOS, as defined above, be less than 0.30. This is an interim standard that should be reviewed and updated as better information becomes available.”* If followed, these guidelines would theoretically create an integrated population that is adapting to natural conditions.

How the HSRG management guidelines, or variations of them, affect the reproductive fitness of natural populations has not been assessed. To do so will be challenging and require, among other things, the capacity to experimentally manipulate the guidelines, presence of reference populations, ability to sample and enumerate juveniles and adults, knowledge of past hatchery ancestry, a program of comprehensive pedigree assessments based on genetic variation, and populations that are large enough to provide adequate samples so that differences can be detected.

The Imnaha River spring Chinook supplementation program, which has been in operation for 31 years, has provided some insights into how supplementation efforts may affect an integrated population.[15] Supplementation has augmented the number of adults returning to the Imnaha River, but there has been no increase in the numbers of natural-origin fish. Additionally, productivity of the natural spawners has decreased since supplementation was initiated. Reduced reproductive success in hatchery fish is one of the factors hypothesized to be responsible for this trend. This reduction was associated with changes in spawn timing, decreases in age of maturation and body sizes, and choice of spawning locations. The PNI value for this population during supplementation has averaged 0.36, substantially below that recommended by the HSRG. Other studies, including ongoing evaluations of spring Chinook supplementation in the upper Yakima River, Umatilla River, Johnson Creek, Snake River Subbasin, and at the Chief Joseph Hatchery plus steelhead research in the Methow River, Hood River, Abernathy Creek, and Grande Ronde Subbasin will provide additional information on how management guidelines may affect integrated populations (e.g., Ann. Proj. Repts. 1989-096-00, 1989-098-00, 2003-023-00, 2003-054-00, 2009-009-00). A synthesis of the information derived from these projects will be needed to address the importance of PNI values in salmon supplementation.

A number of current projects in the Basin may provide incidental information that could increase our understanding of the effects of hatchery supplementation on natural populations. Several projects are monitoring the status and trends of natural populations of spring Chinook and steelhead (Ann. Proj. Repts. 1997-030-00, 2002-053-00, 2010-030-00). These populations could potentially serve as controls, allowing the impacts of environmental conditions in supplemented populations to be separated from the effects due to the addition of hatchery fish. Other projects are evaluating whether hatchery conditions are creating genetic changes in cultured fish. Additionally a few projects are examining how varying percentages of hatchery fish in natural spawning areas may affect the productivity of steelhead and spring Chinook populations (Ann. Proj. Repts. 1991-073-00, 2003-023-00, 2008-105-00, 2012-013-00).

C. Additional Information

We are unaware of any efforts to formally evaluate the effects of the PNI management guidelines currently being recommended by the HSRG on salmonid populations undergoing supplementation. The guidelines are based on evolutionary theory and are logical. Empirical assessments of their effectiveness, however, are needed.

[15] http://orafs.org/wp-content/uploads/2015/03/Session-2-5-Hoffnagle.pdf

2006 Critical Uncertainty 5: Can the carrying capacity of freshwater habitat be accurately determined and, if so, how should this information be used to establish goals and limitations of supplementation programs within subbasins?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #5.

A. Progress and Criticality

Progress–Medium: Methods to determine carrying capacities in freshwater habitats are fairly well established and are either based on habitat features (e.g., Koenings and Burkett 1987, Shortreed et al. 2000, Cramer and Ackerman 2009) or stock recruitment curves. Carrying capacity estimates have been made in a number of subbasins in the Columbia River Basin where hatchery supplementation is taking place (ISAB 2015-1). Consequently progress has been made in developing and using methods to assess carrying capacity. However, it is unclear whether carrying capacity information is helping to shape hatchery goals and refine supplementation in the Basin.

Criticality–High: Criticality was judged to be high because of the importance of establishing juvenile release and hatchery spawner goals for supplementation projects so that productivity of natural populations is not significantly reduced.

B. Contributions from Fish and Wildlife Projects

Two approaches have been used to estimate freshwater carrying capacities of juvenile salmonids in the Basin. The first one quantifies the area of a watershed that is composed of discrete habitat types, such as pools, glides, riffles, and rapids. A standard fish density, obtained from published studies, is assigned to each of these habitat types. These initial density values are subsequently increased or decreased by considering the channel size, substrate type, water depth, cover, and productivity of each habitat unit, e.g., for each individual pool, etc. (Cramer and Ackerman 2009). This method may also consider the effects of light levels, nutrient loading, and the relationship between fish size and territory size (Cramer and Ackerman 2009). Juvenile carrying capacity is estimated by summing the number of fish expected to exist in each habitat type. Climate conditions such as relatively wet or dry years with different temperature regimes will expand or contract the availability of habitat areas. Thus, the juvenile salmonid carrying capacity of a watershed is not fixed but may vary somewhat from one year to the next. Additionally, suitable locations change, often becoming less available, as fish grow which can lead to population bottlenecks (Cramer and Ackerman 2009). Some projects in the Basin are measuring flow, water temperature, and other environmental parameters and assessing juvenile abundance at expected bottleneck periods, e.g. during low summer flow, to estimate juvenile abundance and carrying capacity (e.g., Ann. Rept. 1988-053-00.)

The second method uses stock recruitment curves to estimate carrying capacity (ISAB 2015-1, Ann. Proj. Repts. 1989-024-01, 1989-098-00, 1990-005-01, 1990-055-00, 1991-073-00, 1998-016-00). In this case, the number of adult salmonids spawning in a stream is estimated with estimates of juvenile production. These relationships are used to assess density-dependent effects and estimate carrying capacity (Walters et al. 2013, ISAB 2015-1). Density-dependent effects were found in a number of populations. In the Umatilla subbasin, the abundance of female steelhead adults was negatively related to smolt production and egg-to-smolt survival (Ann. Proj. Rept. 1989-024-01). A similar negative relationship between female abundance and smolt production was detected in spring Chinook in the John Day subbasin (Ann. Proj. Rept. 1998-016-00). Other factors such as scarcity of over-wintering habitat, redd clustering, and limited resource availability appeared to limit juvenile spring Chinook production in Snake River populations (Walters et al. 2013, Ann. Proj. Rept. 1989-098-00). The effects of the Snake River fall Chinook supplementation program on natural-origin parr residing in the Snake River above Lower Granite Dam and in the Lower Granite Dam reservoir were examined. The influx of hatchery juveniles into these habitats reduced growth rates and size of natural fall Chinook juveniles (Ann. Proj. Rept. 1991-029-00).

Many of these projects also investigated how salmonid hatchery supplementation programs affected the productivity, genetic composition, abundance, straying, and distribution of natural- and hatchery-origin fish (Ann. Proj. Repts. 1989-098-00, 1990-005-01, 1995-063-00). A concern commonly expressed in these reports was that downstream habitat conditions were likely limiting the effectiveness of supplementation efforts by reducing the survival of salmonids that moved downstream to new rearing or over-wintering areas prior to smoltification (Copeland et al. 2014). Downstream conditions may limit the expression of life-history diversity as well as overall population abundance. Such areas would be appropriate targets for habitat rehabilitation, if the factors limiting salmonids in these locations are known and can be improved by habitat restoration.

In some instances supplementation programs have been substantially modified by changing: (a) broodstock sources; (b) rearing infrastructure, densities, diets, and feeding regimes; (c) methods for disease prevention; and (d) the date, number, and size of the fish being released. The benefits of acclimation ponds and volitional release strategies have also been investigated (ISRP 2013-3). Results demonstrate success in reducing straying rates and limiting the release of precociously maturing fish or "residuals" in steelhead. Missing in the annual reports, however, were explicit statements of how carrying capacity information has been used to modify supplementation programs. To assess this uncertainty, clear statements are needed on how carrying capacity information has been used or will be used to adjust supplementation programs.

C. Additional Information

Studies in the Basin are tracking changes in environmental conditions within subbasins, assessing effects of habitat restoration, evaluating performance of hatchery origin fish, and determining the effects of hatchery fish on resident biota. A few projects are also generating information on fish populations in streams where supplementation is not taking place. These streams could serve or are serving as important reference sites. Data from such sites can be used to separate the effects of environmental conditions and supplementation efforts on population growth, productivity, smolt-to-adult survival rates and other important metrics. Such information will be needed if carrying capacity data are used to help refine the size of existing and planned supplementation programs.

2006 Critical Uncertainty 6: What is the relationship between basinwide hatchery production and the survival and growth of naturally produced fish in freshwater, estuarine, and ocean habitats?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #6.

A. Progress and Criticality

Progress–Low: Information has been collected that could address this question in tributary, mainstem, estuary, ocean plume, and nearshore ocean habitats. However, progress has been limited because the information has not been organized or analyzed in a manner that directly examines the effects of total Columbia River Basin releases of hatchery fish on natural-origin fish.

Criticality–Priority: More information is needed about the cumulative impacts of hatchery releases on ESA-listed species to help resolve the diverse and sometimes conflicting roles of hatcheries in providing conservation benefits to depressed populations and harvest opportunities.

B. Contributions from Fish and Wildlife Program Projects

No study funded under the Fish and Wildlife Program has directly evaluated the effects of total annual releases of hatchery salmonids on natural-origin fish. However, new tools, such as parentage based tagging, improvements in genetic stock identification (Ann. Proj. Rept. 2008-907-00) and the widespread use of PIT tags and other tagging and marking methods, have made it possible to identify the origin of hatchery- and natural-origin fish wherever they are found. Moreover, data on the numbers of hatchery fish released by species, age, size, dates and location are recorded annually. Portions of fish in these releases are PIT tagged, making it possible to estimate their abundance and their spatial and temporal distributions as they migrate out of the Columbia River Basin. Such estimates may help identify where and when interactions between hatchery and natural-origin fish are likely to occur.

To address this uncertainty, research that examines competitive, predaceous and behavioral interactions between hatchery and natural-origin fish should be partitioned by geographic area (e.g., within tributaries, mainstem reservoirs and so on) and by juvenile and adult life stages. Methods have, for example, been developed and successfully used to investigate how releases of hatchery fish may affect natural-origin fishes in tributary habitats (Pearsons et al. 1998, Pearsons and Hopley 1999, Ham and Pearsons 2001). These procedures have been used in several subbasins. They should be applied in additional subbasins with other species of hatchery fish to broaden our current understanding of the consequences of hatchery releases on natural fish populations.

Additionally, more research is needed to evaluate the impacts of hatchery juveniles on natural fish while both reside in reservoirs (Ann. Proj. Rept. 1991-029-00). For example, given their abundance, do hatchery juveniles deplete food resources, compete with natural-origin fish for food, prey on smaller fishes or instigate a "pied piper" effect inducing natural-origin fish to migrate sooner than expected? The Fish Passage Center collects data on the survival of hatchery and natural-origin PIT tagged salmonids as they move through the Basin's reservoirs. These survival values, coupled with estimates of hatchery smolt abundance, could be used to determine if these two variables are significantly related. Additionally, a substantial amount of information on growth, condition, diet, residency, fish condition, migration rates and survival of juvenile hatchery and wild salmonids in estuary, ocean plume, and nearshore marine habitats has been obtained (*see* Estuary Section). Empirical data produced from these studies could be incorporated into predictive models and used to explore how varying levels of hatchery fish at different times and locations may influence the survival and growth of natural-origin fish. Models of this type would also indicate where additional fieldwork should take place to both refine and validate predictions.

Interactions between hatchery adults and juvenile natural-origin fishes can also occur. Hatchery adults, for instance, can contribute significant nutrients into freshwater and riparian habitats if allowed to spawn naturally or are distributed as carcasses. Yet increasing the abundance of hatchery fish on natural spawning grounds may lower the productivity of natural populations. This has been observed among coho, Chinook and steelhead populations. In a few instances, hatchery fish have been removed entirely from natural populations and this led to increases in the productivity and abundance of the natural populations (Kostow and Zhou 2006, Buhle et al. 2009, Kostow 2011).

C. Additional Information

The collective effect of annual releases of hatchery fish from the Basin's hatcheries on the survival and abundance of natural-origin fish has not been studied extensively. Several studies, however, have examined the combined effect of hatchery releases of steelhead and spring Chinook from Snake River hatcheries on natural-origin counterparts. A negative relationship between release numbers of hatchery steelhead and survival of natural-origin spring Chinook has been observed. The survival of natural-origin steelhead has not been affected, however, by releases of hatchery steelhead. An additional negative relationship between the marine survival of Snake River summer/spring Chinook and the number of hatchery spring Chinook released has been observed in years having poor ocean conditions (Levin et al. 2001, Levin and Williams 2002). Similar analyses using total hatchery release values should be implemented to increase understanding of how hatchery production interacts with the survival and abundance of naturally produced salmonids.

2006 Critical Uncertainty 7: What effect do hatchery fish have on other species in the freshwater and estuarine habitats where they are released?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #7.

A. Progress and Criticality

Progress–High: Methods or approaches on how to limit deleterious interactions between anadromous hatchery salmonids and other species have been tested and are being applied in freshwater habitats. These include changing release dates, altering release locations, using acclimation ponds, implementing volitional release strategies, and establishing hatchery-free zones. Releases of sterilized-hatchery trout at low stocking densities into areas with few wild trout are also taking place in parts of the Basin. This management approach supports recreational fisheries and appears to protect natural populations (Meyer et al. 2012).

Criticality–Medium: The effects of these management approaches have been monitored and evaluated. However, the great abundance of anadromous hatchery juveniles in the Basin (about 140 million are released each year [Fish Passage Center Web site]) increases the likelihood that hatchery fish will encounter and interact with other species. Consequently it is important that the effects of these interspecific interactions with both hatchery- and natural-origin fish continue to be assessed through long-term monitoring efforts.

B. Contributions from Fish and Wildlife Program Projects

Studies in four Columbia River subbasins have investigated whether recently released hatchery fish may affect other species in freshwater habitats. Methods needed for such evaluations appear to be well established. Results indicate that out-migrating hatchery smolts have minimal impacts in the subbasins where they are being released and monitored. A long-running program designed to evaluate the impacts of a spring Chinook supplementation program on native fish species in the upper Yakima River did not detect effects (Ann. Proj. Rept. 1995-063-25). Decreases in steelhead/rainbow trout abundance and biomass were noticed in one of the Yakima River's tributaries; however, these changes could not be definitively associated with the supplementation program (Fast et al. 2015). Studies in the Methow and Wenatchee subbasins have examined potential interactions between reintroduced coho and native spring Chinook, sockeye, and steelhead and used methods similar to those implemented in the Yakima River (Ann. Proj. Rept. 1996-040-00). Again, few effects were detected. A small amount of predation by coho on spring Chinook fry occurred but no predation on sockeye fry was found. Additionally, field observations disclosed that juvenile coho, spring Chinook, and steelhead reared in micro-habitats with differing water velocities and substrates. Consequently, the coho reintroduction program does not appear to have caused juvenile Chinook and steelhead to be displaced from preferred rearing habitats.[16] A different approach was used to examine how a sockeye captive brood program designed to recover

[16] http://www.critfc.org/wp-content/uploads/2013/07/Kamphaus_Mid-Columbia-Coho-Reintroduction-Program.pdfcitation

Redfish Lake sockeye affected natural kokanee in several high elevation lakes. In this case, physical and biological parameters in the nursery lakes were assessed along with trends in abundance, genetic diversity, and distribution of adult kokanee and sockeye. This program has produced enough sockeye adults to allow a conventional hatchery program to develop. Intraspecific competition between kokanee and sockeye was identified as a possible limiting factor to sockeye reintroduction. Diet and genetic analyses along with data on the vertical distribution patterns of kokanee and sockeye are being used to evaluate this possibility (Ann. Proj. Rept. 2007-402-00).

Possible competitive and predaceous effects of hatchery fish on wild salmonids in the Basin's estuary are not well known. Data on arrival timing, residency, growth, diets, and survival of hatchery and wild salmonids in the Columbia River estuary are being collected. However, our understanding of the interactions of hatchery and non-hatchery fish in the estuarine environment is low (Weitkamp et al. 2015).

Potential interactions between recently released juvenile hatchery salmonids and other species will be exacerbated if hatchery fish continue to reside in freshwater habitats. As mentioned in Uncertainty #3, a considerable proportion (often > 50%) of hatchery spring Chinook males may mature precociously (Larsen et al. 2004). Additionally, early maturing or residual steelhead may be produced by hatchery programs. In both cases, management actions have been developed to reduce their occurrence and impacts on native fish species (Snow et al. 2013, ISRP 2013-3, Ann. Proj. Rept. 2002-031-00). However, the extent to which these approaches are used in hatcheries throughout the Basin is not known.

C. Additional Information

The potential effect of hatchery fish on natural fish populations has received a great deal of attention throughout the Pacific Northwest. Many studies have examined whether hatchery fish were preying on other salmonids (e.g., coho and steelhead/rainbow trout on sockeye, pink, and chum salmon fry). A review of 14 studies that examined the incidence of yearling hatchery fish predation on wild subyearling salmonids in freshwater rivers and streams indicated that the percentage of wild subyearling salmon preyed upon by yearling salmonids was generally low (Naman and Sharpe 2011). However, if a large proportion of the natural subyearling population was present and small enough to be vulnerable to predation when hatchery yearlings were released, then the proportion of the wild population lost to predation could be substantial. This review also indicated that management actions can minimize predation rates by reducing the spatial and temporal overlap of hatchery and wild salmonids. Predation is only one of the risks posed by releasing hatchery salmonids. Competition for food, space, or other resources is likely. Evaluations in ocean habitats indicate that large releases of hatchery fish reduce the individual size and abundance of natural salmon populations (e.g., Ruggerone et al. 2011) and that the potential for resource competition in estuaries is also high.

Whether hatchery fish are important pathogen vectors remains an open question. This concern was explicitly examined in the Yakima subbasin, and no deleterious effects were noted (Fast et al. 2015). Recently developed genetic methods should make it possible to track pathogen transmission in a more sophisticated fashion. It is hoped that these new tools will be used to investigate this issue.

Although not covered in any of the Annual Project Reports, interactions between hatchery trout (e.g. rainbow trout, brown trout, and brook trout) released into natural environments with native trout and non-game fishes is an important management topic (ISAB 2015-1). Fish and wildlife agencies have recognized that introductions of non-native trout can replace native trout species through predation, competition, and hybridization.[17] Management actions such as releasing only sterile hatchery trout at low stocking densities in areas with few native trout are being implemented in parts of the Basin (Meyer et al. 2012); these actions appear to have ameliorated potential impacts on native fishes. However, higher stocking densities and releases of hatchery fish at multiple and prolonged periods into the same receiving habitat may impact native fish species (Meyer et al. 2012).

[17] For example, see www.dfg.ca.gov/fish/Resources/WildTrout/WT_NativeTrout.asp.

Hydrosystem

Table 3. Hydrosystem-theme[18] critical uncertainties in the 2006 Research Plan and the number of Fish and Wildlife Program projects that directly or potentially addressed each one.

ID	2006 Research Plan Critical Uncertainty (click on link to see specific projects)	Directly	Potential
8	What is the relationship between levels of flow and survival of juvenile and adult fish through the Columbia Basin hydrosystem? Do changes in spill and other flow manipulations significantly affect water quality, smolt travel rate, and survival during migration? How do effects vary among species, life-history stages, and migration timings? What is the role of hydrodynamic features other than mid-channel velocity in fish migration? What is the relationship between ratios of transport, inriver return rates, and measurements of juvenile survival (D values)?	8	11
9	Under what conditions is delayed mortality related to downstream migration through the hydrosystem, and what is the magnitude of that delayed mortality?	5	2
10	What are the effects of multiple dam passages, transportation, and spill operations on adult fish migration behavior, straying, and pre-spawn mortality, and juvenile-to-adult survival rates?	5	27
11	What is the effect of hydrosystem flow stabilization, flow characteristics, and channel features on anadromous and resident fish species and stocks? What are the ecological effects of hydrosystem operations on downstream mainstem, estuarine, and plume habitats and on populations of fish and wildlife?	2	12
12	What are the optimal temperature and water quality regimes for fish survival in tributary and mainstem reaches affected by dams, and are there options for hydrosystem operations that would enable these optimal water quality characteristics to be achieved? What would be the effects of such changes in operations and environment on fish, shoreline and riparian habitat, and wildlife?	5	9

Summary

Projects in this theme have contributed for many years to the extensive evaluation of various impacts of the hydrosystem on fish and wildlife, such as passage survival of salmonids through individual dams. Hydrosystem fish passage projects have mostly relied upon PIT tagging and efforts are being made to add more PIT tag detectors to dams (e.g., on spillways or in fish ladders), in natal streams (e.g., instream arrays), and in the estuary (e.g., towed arrays or on pile dikes). Fish passage over individual dams also

[18] See the 2006 Research Plan summary for further background information on this theme, pages 13-14; and the 2014 Fish and Wildlife Program strategies on mainstem hydrosystem flow and passage operations.

has been evaluated using acoustic- and radio-tagged fish to measure routes of passage and survival rates. Less work has been conducted to estimate abundance of smolts (both tagged and untagged) passing through the entire hydrosystem. Tracking the abundance of smolts as they move through the hydrosystem is important because it will: (a) allow detection of potential density-dependence effects due to habitat restoration activities, and (b) indicate cumulative total losses of smolts in each reservoir. To estimate abundance, PIT-tagged fish monitoring must be augmented with additional surveys (such as parentage based tagging) to assess the total spatial and temporal distribution of smolts. Lifecycle models (e.g., Comparative Survival Study 2015, NOAA Fisheries Life Cycle Model) could be used to integrate information from PIT-tagged fish and production to model abundance of salmonids moving through the hydrosystem.

More work is needed on evaluating the passage and survival of returning adults (e.g., determining where mortality occurs, how much straying occurs, and the effects of covariates such as temperature on survival). The major limitation in such studies is the scarcity of tagged returning adults of known origin. Most studies rely on surviving adults tagged as juveniles. Other projects have added radio tags on returning adults to improve detection efficiencies and evaluate migration behavior. Some potential gains in efficiency could be obtained if adult fish were intercepted, their stock status determined by genetic stock identification (GSI), and then followed after being released with tags (either PIT or radio).

With more than 20 years of data, projects have evaluated the impacts of covariates, such as spill or water temperature, on various smolt performance measures. These projects mostly have been observational studies, but their results have given rise to a proposed experiment to investigate how smolt-to-adult survival is affected by a deliberate increase in the magnitude and duration of spill. While this work is laudable and fairly comprehensive, the largest source of mortality and greatest source of uncertainty about the relationships between covariates and survival occurs during the period of ocean residence. Some investigations have attempted to detect PIT tagged fish in the estuary using towed arrays, but detections have been low. Much additional research (including developing new monitoring tools) is needed to identify factors that impact survival in the estuary and early in the period of ocean residence, and management actions that may be possible (e.g., modifying spill and flow to speed/slow fish from entering the estuary). Some studies have looked at juvenile salmonids in the estuary and during early ocean residency (e.g., POST, Jackson 2001, JSAT network, McMichael et al. 2010), but these studies have now stopped. The only study currently examining salmonid survival in the plume and ocean is NOAA's ocean survival study (Ann. Proj. Rept. 1998-014-00).

The question of differences in delayed mortality between transported and in-river migrating fish has been investigated for about 10 years by examining smolt-to-adult returns (SARs). NOAA researchers are still investigating the seasonal effects of transportation on a species-by-species basis, and its effects remain unresolved. Moreover, Hostetter et al. (2015) has indicated that juvenile bypass systems tend to select smaller size smolts and juvenile fish in poorer condition compared to fish that use spillway or turbine systems, which may confound transportation and condition effects. This difference in bypass selectivity based on fish size and condition may explain the lack of a consistent benefit from transport throughout the spring season because juvenile bypass systems are used to collect fish for transport (i.e., transported fish may have experienced higher mortality in-river if they were not transported). Further studies on this question would benefit from incorporating multiple populations, multiple collection locations, and multiple years to address these additional complexities.

Information on hydrosystem effects on other species (e.g. Pacific lamprey) has been limited by the lack of suitable tags. However, recently developed methods (such as smaller tags or genetic methods) for tagging other species, such as lamprey offer considerable promise.

Information on hydrosystem effects on white sturgeon is also limited because of the long lifespan of these fish and the difficulty in sampling them. They also are not yet a listed species in the lower Columbia River.

2006 Critical Uncertainty 8: What is the relationship between levels of flow and survival of juvenile and adult fish through the Columbia Basin hydrosystem? Do changes in spill and other flow manipulations significantly affect water quality, smolt travel rate, and survival during migration? How do effects vary among species, life-history stages, and migration timings? What is the role of hydrodynamic features other than mid-channel velocity in fish migration? What is the relationship between ratios of transport, in-river return rates, and measurements of juvenile survival (D values)?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #8.

A. Progress and Criticality

It is challenging to assign a single level of progress and criticality to this collection of uncertainties related to hydrosystem operations and impacts. Advancing knowledge on the impacts of hydrosystem operations remains critical for evaluating the performance of dams in passing fish relative to BiOp standards and for identifying mitigation requirements.

***Effect of spill and flow on juvenile and adult survival*:**

Progress–Mixed: Progress is judged to be high on evaluating the impact of flow and spill on juvenile survival. The CSS reports have found statistical relationships between spill and flow on juvenile survival of Snake River spring Chinook and steelhead that are based on almost 20 years of data. While these results are correlational and not causal, the relationships appear to be consistent. Hydrosystem impacts have the potential to be large and information collected identifies specific dams that fail to meet performance measures and where bottlenecks occur in the system.

Progress is judged to be medium for impacts of flow and spill on returning adult survival through the hydrosystem. These studies are typically limited by the availability of PIT-tagged juvenile fish returning as adults. In the past, this aspect was assumed to be less critical given the believed relatively high survival rates of adults as they migrate up the hydrosystem, but more recent studies have found higher mortality and increased pre-spawning mortality, especially with warmer water. These recent events with warmer water may provide important information on future impacts of climate change. It is important to understand adult survival and behavior (e.g., straying and pre-spawning mortality) as the fish approach terminal areas to ensure that performance meets BiOp standards and to help manage hatchery and wild fish on the spawning grounds.

Criticality–High: Criticality was judged to be high for the effects of flow and spill on juvenile and adult survival as these operations are key for evaluating the performance of dams in passing fish relative to BiOp passage standards and for identifying mitigation requirements.

Effect of spill and flow on smolt travel rate and water quality

Progress–High: Progress is judged to be high for the impact of changes in spill and other flow manipulations, on smolt travel rate, survival during migration and water quality, especially with respect to total dissolved gasses. Spill and flow manipulations are the key management tools for moving smolts through the hydrosystem, and recent studies have demonstrated improvements in survival and reductions in smolt travel times under certain spill regimes. Spill is carefully managed to keep total dissolved gas levels in the river within acceptable ranges.

Criticality–High: Criticality was judged to be high for examining the effects of changes in spill and flow on smolt travel rates, smolt survival, and water quality. These performance measures directly relate to the success of fish passing through the hydrosystem.

Varying effects among species, life history stages and migration timings

Progress–High: Progress is judged to be high for understanding how effects of flow and spill vary among species, life-history stages, and migration timings as reported in the CSS studies and compiled by NOAA researchers.

Criticality–Medium: Criticality was judged to be medium for understanding how different species were influenced by flow and spill operations. Different species and/or life stages may respond differently to changes in flow or spill and it is important to avoid unintended consequences.

Role of hydrodynamic features

Progress–Low: Progress is judged to be low on examining the role of hydrodynamic features other than mid-channel velocity in fish migration. We are unaware of any studies in our review that examine this question other than some studies of smolt use of backwater and side channel habitat areas in the lower Columbia River and estuary.

Criticality–Low: Criticality was judged to be low for examining the effects of hydrodynamic attributes on fish migration as it is believed that most emigrating fish (e.g., yearling migrants) respond to the mid-channel velocity. However, subyearling Chinook like to rear along the margins of the mainstem and in off channel habitats and thus could be affected by changes in flow and river velocity.

Impact of transportation

Progress–High: Progress is judged to be high for the impact of transportation. There are now over 10 years of data (CSS report and NOAA fisheries, Smith et al. 2013) on the impact of transportation on survival of juveniles. The CSS results fail to show a consistent benefit of transportation. Smith et al. (2013) found that benefits of transportation tend to increase over the season and over the entire season the benefits tended to be positive. However, another project (Hostetter et al. 2015) concluded that fish selected for transport maybe smaller and not as fit as those fish which were not bypassed which could explain some negative findings.

Criticality–Medium: Questions still remain about the seasonal benefits of transportation, particularly since previous comparisons may have been compromised due to differences in fish size and condition (Hostetter et al. 2015). While the work conducted to advance knowledge on this uncertainty is laudable, the largest source of mortality and greatest source of uncertainty about the relationships between covariates and survival occurs during ocean residence. Yet adult production also depends on juvenile survival through the hydrosystem. If survival is low, the number of smolts that could potentially return as adults will be reduced from what it might have been in both good and poor ocean years. Consequently, the seasonal, stock-specific benefits from transportation have some importance and are worthy of further investigation.

B. Contributions from Fish and Wildlife Program Reports

The Comparative Survival Study (CSS) is a long running project that examines the relationships of flow and spill on survival of juvenile fish and their travel time through the hydrosystem. Based on almost 20 years of data, regression models have been used to determine relationships of flow and spill on survival and travel time. While the relationships are statistical (and may not be causal), the CSS believes the results make a compelling case for modification of flow and spill to improve juvenile survival. This study analyzed groups of juvenile salmonids from the Snake River Basin including yearling spring/summer Chinook salmon, subyearling (fall) Chinook salmon, steelhead and sockeye salmon. It also analyzed yearling spring/summer Chinook salmon, sockeye salmon, and steelhead originating in the upper Columbia River, from Rock Island Dam to McNary Dam. Data are available for individual release cohorts within the same year, which differ in their migration timings. The CSS project requires a high level of cooperation and coordination among stakeholders in the Basin who have an interest in the results of the CSS. While some work has been undertaken to investigate the optimal allocation of tagging (IEAB 2013-1), more work is needed on deciding where the next marginal dollar should be spent.

Smith et al. (2013) also analyzed several years of data (1998 to 2009) where SARs of juvenile fish that were transported from Lower Granite Dam (LGR) were compared to SARs of those that were bypassed at Lower Granite Dam and continued in-river migration through the lower Snake and Columbia Rivers. In each year, there were potentially 16 different data sets for fish passing LGR, resulting from the combinations of two species (spring/summer Chinook and steelhead), two rearing types (wild and hatchery), two release areas (all sites upstream from LGR and in the tailrace at LGR), and two passage histories (transported or bypassed). The analysis was done at a daily or weekly level (if numbers of fish were very small). Flow, spill, and water temperature were among the covariates used in a regression analysis of the SAR values.

Smith et al. (2013) found that with some exceptions, the estimated benefit of transportation was usually nearly constant throughout the season for steelhead or steadily increasing for both wild and hatchery Chinook salmon. In several years, the estimated benefit of transportation increased late in the season when SARs for both groups of Chinook were decreasing, indicating that the decline for bypassed Chinook was steeper than for transported fish. Estimated benefits of transportation for wild steelhead were relatively constant throughout the season for 8 of the 10 migration years. There was one year when estimated benefits decreased through time and one year when it increased. Hatchery steelhead exhibited more variation in patterns of transportation benefits.

The CSS has also collected and analyzed the effects of transportation on ocean going smolts. Based on adult returns of fall Chinook to Lower Granite Dam (LGR), there appears to be no consistent benefit from transport based on 6 years of returns. As of 2015, twelve study cohorts of subyearling fall Chinook salmon showed significant benefit to adult returns when migrating in-river whereas only five cohorts showed a significant transport benefit. Overall, 32 cohorts showed no evidence of a benefit to transportation. The CSS concluded "*Based on transport/in river ratio of SARS [ed] (TIR)s of adult returns to LGR it appears that the juvenile smolt transportation program does not mitigate for the adverse impacts of the operation of the Federal Columbia River Power System[ed] (FCRPS) on fall Chinook groups…*"

There has been less emphasis on factors addressing adult migration upstream through the hydrosystem, primarily because it is believed that survival of returning adults moving up the hydrosystem is high. Several projects (e.g., AFEP, 2008-908-00, Ann. Proj. Repts. 2008-518-00 and 2012-013-00) collect data that could be used to assess migrating adults through the hydrosystem and in terminal areas. These studies are typically limited by the availability of PIT-tagged juvenile fish returning as adults. There does not appear to be the same degree of coordination among the project sponsors (BPA, USACE, mid-Columbia Public Utility Districts (PUDs) upstream) as found in the CSS. Improved coordination may allow adult passage studies to be done at larger spatial scales and to "share" tagged fish among studies.

Much more work has been conducted on the fate of adult fish as they approach terminal areas (e.g., documenting straying) because of the relative ease and duration of sampling. Most assessments of straying, however, have used hatchery fish. Information on straying of natural-origin fish is much more limited. Further information about this topic is found in the description of projects under the 2006 Uncertainty #10 "*What are the effects of multiple dam passages, transportation, and spill operations on adult fish migration behavior, straying, and pre-spawn mortality, and juvenile-to-adult survival rates?*" Not as much work, however, has been done to examine the effects of dam passage and mainstem conditions on the occurrence, frequency, and causes of pre-spawn mortality.

There has been little investigation of impacts of flow and spill on water quality other than on dissolved gases and temperature. In light of potential effect of climate change on water temperature, additional modeling work is needed on the impacts of hydrosystem management on water temperatures in the mainstem Columbia and Snake rivers.

C. Additional Information

Numerous ISAB reports have reviewed the CSS (e.g., ISAB 2015-2) and AFEP projects. Generally speaking, these reviews noted that the annual CSS report is a mature product, typically including only updates with the latest year of data and expansion of analyses as more data are acquired. Many of the methods have been reviewed in previous ISAB reports and so now receive only a cursory examination. As more data are acquired, new questions arise on the interpretation of the results—this is now the focus of current ISAB reviews.

IEAB 2013-1 and ISAB 2013-3 has reviewed allocation of tagging resources at a general scale and concluded that "*current programs are fairly decentralized, and yet positive spillover effects and coordination benefits exist at many levels. Taking advantage of wide-ranging mutual benefits represents a complex coordination problem. A rationalization program could both improve program efficiency and bring about cost savings at the same time.*"

2006 Critical Uncertainty 9: Under what conditions is delayed mortality related to downstream migration through the hydrosystem, and what is the magnitude of that delayed mortality?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #9.

A. Progress and Criticality

As stated, this uncertainty is not answerable (and predated the ISAB 2007-1 review, see below) because it is impossible to have a control group of fish with no dam passage in an unmodified hydrosystem. Indeed, ISAB 2007-1 stated, "*The ISAB concludes that the hydrosystem causes some fish to experience latent mortality, but strongly advises against continuing to try to measure absolute latent mortality. Latent mortality relative to a dam-less reference is not measurable. Instead, the focus should be on the total mortality of in-river migrants and transported fish, which is the critical issue for recovery of listed salmonids. Efforts would be better expended on estimation of processes, such as in-river versus transport mortality that can be measured directly*." Projects have instead studied a related measure of differential delayed mortality – comparing the effect of transportation vs. in-river migrating fish on adult return rates.

This uncertainty overlaps with 2006 Uncertainty #8 *"…. What is the relationship between ratios of transport, in-river return rates, and measurements of juvenile survival (D values)?*"

Progress–High: Progress has been judged to be high when measuring differential delayed mortality using the ratio of ocean survival of transported fish to in-river migrating fish ("*D*") among Snake River fish after they pass Bonneville Dam. There have been only limited studies of the effects of transportation on other stocks.

One limitation in investigating the impact of in-river vs. transportation on survival is the lack of spillway detection for PIT-tagged fish. Several projects are exploring the development of spillway detection systems but logistical constraints (e.g., electrical interference from the dam materials on the spillway on the ability of the PIT-array to detect fish) have limited this effort.

Criticality–Medium: Criticality was judged to be medium because the largest source of mortality and greatest source of uncertainty about the relationships between covariates and survival occurs during ocean residence. There remains some uncertainty about the seasonal benefits of transportation that require some additional research. Current findings from the CSS indicate only modest benefits from transportation and Smith et al. (2013) indicated that transport benefits exhibited seasonal patterns. The reason for these different findings needs to be studied and explained further.

B. Contributions from Fish and Wildlife Program Projects

Differential delayed mortality is primarily investigated by using the ratio of transported to in-river migrating fish ocean survival of Snake River fish after they pass Bonneville Dam ("D"). The primary sources of information on delayed mortality are the CSS projects and the NOAA transport studies (Smith et al. 2013). The CSS concluded that "*Estimated D values for subyearling Snake River fall Chinook were below 1, for nearly all groups in the years 2006 to 2012. That was similar to patterns seen in yearling Chinook and steelhead (hatchery and wild groups) in the same years. A longer time series for subyearling Chinook would be helpful to determine if D estimates would have been higher prior to 2005 (the beginning of court-ordered summer spill) similar to the pattern seen for hatchery and wild steelhead groups that had D values that were well above 1 for several years prior to 2006.*" Smith et al. (2013) found that with some exceptions, the estimated benefit of transportation was nearly constant throughout the season for steelhead but steadily increasing for both wild and hatchery Chinook salmon. In several years, the estimated benefit of transportation increased late in the season while SARs for both groups of Chinook were decreasing, indicating that the decline for bypassed Chinook was steeper than for transported Chinook. Estimated benefits of transportation for wild steelhead were relatively constant throughout the season for 8 of the 10 migration years. There was one year when estimated benefits decreased through time and one year when it increased. Hatchery steelhead exhibited more variation in patterns of transportation benefits. The reason for these differential findings is unknown.

Hostetter et al. (2015) showed that juvenile bypass systems tend to select smaller juvenile fish and fish in poorer condition compared with fish that use the spillway or turbine systems. Because the juvenile bypass system is used to select fish for transport, this may help explain the inconsistent effects of transport. This difference in condition may explain the lack of a consistent, detectable benefit from transport because juvenile bypass systems are used to collect fish for transport (i.e., transported fish may have experienced higher mortality in-river if they were not transported).

These two findings suggest that a series of carefully planned experiments is needed to clarify whether high delayed mortality of transported fish is an artifact of non-random bypass selectivity of fish. The project titled *Evaluate Delayed (Extra) Mortality Associated with Passage of Yearling Chinook Salmon through Snake River Dams (2003-041-00)* is not complete, but it will compare return rates for three groups of fish (transferred by truck and released below Ice Harbor Dam; transported an identical amount of time by truck before release into the Lower Granite Dam tailrace; and released into the Lower Granite Dam tailrace without having been transported by truck). These results should be available in 2016 and should be considered when designing the follow-up experiment to investigate the impact of non-random use of fish on the delayed mortality of transported fish.

C. Additional Information

The ISAB and ISRP have reviewed CSS and AFEP projects many times. Indeed, ISAB 2007-1 concluded that efforts should be made to compare the total mortality of in-river migrants to that experienced by transported fish. These investigations are currently occurring (Ann. Proj. Rept. 2003-041-00) with results expected in 2016.

2006 Critical Uncertainty 10: What are the effects of multiple dam passages, transportation, and spill operations on adult fish migration behavior, straying, and pre-spawn mortality, and juvenile-to-adult survival rates?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #10.

A. Progress and Criticality

Progress–High: Reliable data are available on juvenile-to-adult survival (SARs) for many species and at a relatively fine geographic scale (dams) in the hydrosystem. The associations among SARs and hydrosystem factors (e.g., spill and flow) and other factors (e.g., ocean conditions) also have been investigated. Key limitations are the necessity of tagging large numbers of juveniles with PIT-tags to ensure that sufficient numbers of adults return to Bonneville Dam to measure SARs with appropriate resolution. Existing genetic stock identification methods could be used to obtain more information on the upstream survival of adults originating from different stocks. Un-tagged adults intercepted at mainstem dams could be DNA sampled, tagged and released. Once stock identification had been established it could be linked to a tag (e.g., PIT tag number or radio tag) and subsequent detections at dams and instream arrays could be used to assess survival, migration, and straying rates. A feasibility analysis should be undertaken.

Currently, adult behavior is collected on tagged fish as they migrate up the hydrosystem and from passage at the final dam to spawning areas. The key limitation in these above-dam studies is the ability to detect fish. Local PIT antenna-arrays, fences, or weirs are often used and further methodological development is needed.

Criticality–High for SARs: SARs are the primary metric used to judge if a stock is self-sustaining. Changes in SARs due to hydrosystem effects have some potential to be mitigated through management actions. Changes in SARs due to ocean conditions and/or climate change are less amenable to adjustments through management actions, though it is recognized that migration timing and fish size and condition may influence survival at sea.

Medium criticality for adult behavior because much of the information is currently collected but not organized for easy retrieval. More information on adult behavior as they approach spawning areas or hatcheries is needed to identify sources of pre-spawning mortality and unsustainable populations.

B. Contributions from Fish and Wildlife Program projects

The CSS is a major source of information and analysis on juvenile-to-adult survival rates (SARs) with 10-20 years of data, depending on stock. The analysis includes Snake River wild and hatchery spring/summer Chinook and steelhead. Recent work has reported SARs at finer geographic scales. Ongoing work also estimates SARs of wild spring/summer Chinook groups and A-run and B-run steelhead from the Grande Ronde/Imnaha, South Fork Salmon, Middle Fork Salmon, Upper Salmon, and Clearwater Major Population Groups.

Keefer and Caudill (2012, 2014) provide an extensive review of the mechanisms responsible for straying and its occurrence by anadromous salmonids with an emphasis on Columbia River populations. Evidence from tagging studies indicate higher straying rates in adults that were transported as juveniles compared to those that migrated in river, potentially hindering salmon and steelhead recovery efforts. A clear understanding of the patterns of straying across populations and the underlying mechanisms affecting upstream migration behavior, route selection, and homing to (or straying from) natal habitats is critical to evaluating the effects of induced straying on salmon and steelhead populations. Two important uncertainties include specific mechanisms that impair imprinting of transported juveniles and interactive effects such as rearing history. Candidate hypotheses for mechanisms include chronological effects (i.e., transport is too rapid), spatial effects (i.e., barges are moving in inappropriate habitats), and in-barge effects (i.e., stress, contaminants, pathogen transmission, etc.). Interactions between hatchery rearing and juvenile transport are poorly understood. A statistical model was developed for straying rates of Snake River steelhead (Keefer and Caudill 2012).

Other projects investigate adult migration to terminal areas by examining stray rates and investigating differences in conversion rates and pre-spawn mortality as functions of hydrosystem covariates. Often the studies are limited by (1) insufficient numbers of adults tagged with PIT-tags as juveniles and (2) limited PIT tag detection systems at mid- and upper Columbia PUD dams and upstream tributaries such that sources of mortality cannot be identified. Here genetic stock identification methods would allow adults to be sampled, identified as to stock of origin, tagged and released; thereby increasing sample size and temporal resolution of estimates. Improved detection methods would assist in determining sources of mortality. While coordination with the CSS project is necessary for hydrosystem detections and analysis, the CSS does not provide a common database and analysis platform for data collected from adult fish as they move to spawning areas above the last dam. The resulting fragmentation of effort, reporting, and data storage among groups studying fish in terminal areas may require additional coordination to ensure that information on all relevant stocks is available to all research groups.

C. Additional Information

The CSS, AFEP, and related projects have been reviewed in numerous ISAB/ISRP reports (e.g. ISAB 2015-2). These reviews have generally been satisfied with analyses performed in subsequent annual reports. The IEAB (IEAB 2013-1) has reviewed allocation of tagging resources for outgoing smolts but did not consider adult returns.

2006 Critical Uncertainty 11: What is the effect of hydrosystem flow stabilization, flow characteristics, and channel features on anadromous and resident fish species and stocks? What are the ecological effects of hydrosystem operations on downstream mainstem, estuarine, and plume habitats and on populations of fish and wildlife?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #11.

A. Progress and Criticality

This uncertainty has two separate questions with only a limited relationship between the two parts.

Progress–Medium: Progress is judged to be medium for both parts. BPA, USBR and the mid-Columbia PUDs conducted many flow stabilization studies in the Hanford Reach below Priest Rapids Dam. Harnish et al. (2012) and Harnish et al. (2014) examined the impacts of regulating hydrosystem operations. Regulations to prevent dewatering of redds and to limit stranding and entrapment of juveniles led to large increases in productivity. Under the Vernita Bar Agreement, the mid-Columbia PUDs and Bonneville agree to maintain a minimum outflow from Priest Rapids Dam of 70,000 cubic feet per second, which would provide a guaranteed amount of spawning habitat in the river.

Hatten et al. (2009) found that tailwater fluctuations can shift availability and reduce the amount of suitable spawning habitat within the mainstem channel.

Geist et al. (2008) and Poirier et al. (2012) examined whether fluctuations in Bonneville Dam tailwater elevation were related to chum salmon spawning activities in three tributary spawning areas. Increased Bonneville Dam tailwater elevation was associated with later and longer lasting chum salmon spawning activities. Because the regulation of tailwater elevation downstream from Bonneville Dam can influence spawning of chum salmon in adjacent tributaries, the extent to which this is a causal factor in the decline of chum salmon in the Columbia River is unclear.

Some modifications to flow regimes have been suggested to improve spawning and rearing habitats based on detailed surveys of habitat usage. These spawning and rearing habitats are critical for the focal species. A related 2006 Uncertainty discusses similar issues (#15 “*Habitat: What are the impacts of* *hydrosystem operations on mainstem habitats, including the freshwater tidal realm from Bonneville Dam to the salt wedge? How might hydrosystem operations be altered to recover mainstem habitats?")*.

Many studies have investigated the effects of flow and spill on migrating juvenile and adult salmon, but little work has involved native resident fish species.

Criticality–Medium: Criticality was judged to be medium for both parts. Current operations are based on previous flow studies to avoid major deleterious effects such as dewatering. The primary focus of many studies has been on impacts to migrating juveniles in the hydrosystem rather than on ecological impacts in the estuary and plume where direct hydrosystem impacts are thought to be smaller.

B. Contributions from Fish and Wildlife Program Projects

Projects 1994-033-00 (Fish Passage Center) and 1996-020-00 (CSS report) modeled the role of flow and spill on migrating juvenile and adult salmonids but did not examine other impacts of flow stabilization.

Other projects appear to be local efforts where specific changes to flow are suggested to improve habitat or control predators, but no evaluation or data were collected on the impacts of flow change.

Two projects provide information about impacts of the hydrosystem in the lower Columbia River and estuary. Project 1999-003-01 determined what conditions (operational and physical habitat features) must exist to provide successful spawning and rearing for salmonids below lower Columbia River mainstem dams and what measures must be taken to protect chum and fall Chinook salmon spawning. Project 2003-007-00 provides dissolved oxygen, temperature, and conductivity data at habitat and fish monitoring locations that can be related to hydrosystem operations.

There does not appear to be coordination among these projects. As such, it is not clear how changes in flow at one project may impact fishes and habitats farther downstream.

C. Additional Information

There have been ISAB reviews on this topic (e.g., ISAB 2004-2) which concluded that *"No 'passive' design for measuring downstream effects of the proposed change in flow/spill is likely to be effective in a reasonable period of time. Deliberate experimental flow manipulations of an amplitude considerably larger than flows that will result from the Amendments probably would allow empirical quantification of flow effects. Whether or not present institutional constraints would allow such manipulations, however, is an open question."* These same limitations persist today.

2006 Critical Uncertainty 12: What are the optimal temperature and water quality regimes for fish survival in tributary and mainstem reaches affected by dams, and are there options for hydrosystem operations that would enable these optimal water quality characteristics to be achieved? What would be the effects of such changes in operations and environment on fish, shoreline and riparian habitat, and wildlife?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #12.

A. Progress and Criticality

Progress–High and Low: Progress is judged to be **high** on examining the effects of temperature and water quality on salmonid (and related species) behavior and mortality from laboratory studies, especially the deleterious effects of high water temperatures. However, the level of progress on the spatial distribution of water temperature in the rivers and locations of thermal refuges is judged to be **low**. Uncertainty #13 ("*To what extent do tributary habitat restoration actions affect the survival, productivity, distribution, and abundance of native fish populations?*") also reviews projects where habitat restoration activities may modify stream temperatures.

Progress is judged to be **low** on assessing the impact of changes in hydrosystem operations on fish, wildlife, and shoreline and riparian habitat. We are unaware of any projects in our review that considered this question.

Progress is judged to be **low** on ascertaining the effects of temperature on white sturgeon. Given the long lifespan of these fish, this will be difficult to study (i.e., to detect an increase in mortality or reduction in spawning in sub-optimal temperature regimes). Modeling studies may be helpful in this area where fish response to elevated temperatures is studied using bioenergetics models.

Criticality–Medium: Management actions in the hydrosystem may be able to mitigate some changes in the mainstem (e.g., releasing cold water from storage reservoirs), but there is limited management scope in terminal areas upstream. The forecasted impact of management actions may not be well understood as climate change may move the system into an altered flow/temp regime. Given that increase in water temperature is one of the projected impacts of climate change, water temperature is critical information needed to better predict impacts on populations. The assumed relationship between temperature and species behavior and mortality is the basis for many habitat restoration activities such as establishing riparian vegetation to reduce temperatures in streams.

B. Contributions from Fish and Wildlife Program Projects

The CSS modeled the impact of water temperature on travel times and found limited support for the effect of temperature in two mainstem reaches (e.g., lower Snake and lower Columbia rivers) for yearling juvenile Chinook salmon. It found evidence of a deleterious effect of increased temperature on survival, with pronounced effects on juvenile sockeye and steelhead in the same two mainstem reaches. These are natural experiments, and so many confounding variables are present.

Faulkner et al. (2015) compared daily differences in travel speed to the estuary relative to changing river flow volume and between transported and inriver migrating fish. Overall, seasonal mean travel speed to the estuary was significantly slower for yearling Chinook salmon released from barges than for those traveling inriver and detected at Bonneville Dam. Mean travel speed was also significantly slower for steelhead released from barges than for those detected at Bonneville Dam on the same day. These differences in travel speed by migration history, particularly for yearling Chinook salmon, were similar to observations from the previous year. They did not, however, explicitly model the impact of water temperature on survival or migration time even though these data were available.

Project 2002-032-00 contained a component that investigated the impact of water temperature on the consumption of salmonids by smallmouth bass, with higher water temperatures leading to increased consumption. Project 2010-076-00 measured reach survival and water temperature, but a relationship between these two variables was not detected, most likely due to the short duration of the project.

We are unaware of any Fish and Wildlife Program projects that have investigated impacts of hydrosystem operations on shoreline habitat, riparian habitat, and wildlife.

Projects 2003-007-00 and 1987-100-02 are opportunistic studies where many habitat attributes are measured with the long-term goal of trying to relate habitat characteristics with fish performance (e.g., survival or travel time). Few studies can directly manipulate temperature or water quality in the field.

C. Additional Information

There is substantial literature addressing the impact of temperature (and other environmental conditions) on salmon. For example, National Research Council (2004) reviewed the impacts of flow, temperature, and other environmental conditions in the Columbia Basin. Isaak and Rieman (2013) estimated isotherm shift rates in streams that can be used to represent historic or future warming scenarios. Roni et al. (2012) is an example of a study looking at impacts of temperature and other factors on two streams on the Olympic Peninsula.

Tributary and Mainstem Habitat

Table 4. Tributary and mainstem habitat-theme[19] critical uncertainties in the 2006 Research Plan and the number of Fish and Wildlife Program projects that directly or potentially addressed each one.

ID	2006 Research Plan Critical Uncertainty (click on link to see specific projects)	Directly	Potential
13	To what extent do tributary habitat restoration actions affect the survival, productivity, distribution, and abundance of native fish populations?	17	41
14	Are the current procedures being used to identify limiting habitat factors accurate?	12	33
15	What are the impacts of hydrosystem operations on mainstem habitats, including the freshwater tidal realm from Bonneville Dam to the salt wedge? How might hydrosystem operations be altered to recover mainstem habitats?	1	9
16	What pattern and amount of habitat protection and restoration is needed to ensure long-term viability of fish and wildlife populations in the face of natural environmental variation as well as likely human impacts on habitat in the future?	9	37

Critical uncertainties #13 and #14 are addressed together because two large projects address them as a set, the Columbia Habitat Monitoring Program (CHaMP) and the Integrated Status and Effectiveness Monitoring Program (ISEMP).

Overview of Ongoing Projects Addressing the Question and Additional Information

See Tables of FY 2015 projects addressing CU #13 and CU #14.

A. Progress and Criticality

Progress–Medium: Much has been learned about how habitat restoration at the reach scale affects fish abundance, short-term measures of growth, and in some cases survival, over a few seasons at most (e.g., from fall to spring; less is known about winter conditions). However, much less has been learned about how the aggregate effects of restoration at watershed scales affect abundance, growth, and survival throughout the entire life cycle of anadromous salmonids (CU #13) and resident salmonids in the inland portions of the Basin. This is primarily because of the large scales of space and time over which habitat and fish must be measured, even for resident fish, and because of interactions among the many factors that fish encounter at these scales. Furthermore, because of the large scales, relatively little is known about whether current methods used to measure habitat are accurate (CU #14).

[19] For further background on this theme, see the 2006 Research Plan summary pages 14-15 and the 2014 Fish and Wildlife Program strategy on Strongholds.

Criticality–Priority: A key assumption of the Fish and Wildlife Program is that improvements in tributary and mainstem habitats will mitigate for reduced survival and growth caused by hydrosystem dams, reservoirs, and operations. Therefore, CU #13 (how much the restoration of tributary and mainstem habitats can increase fish abundance and productivity, and thereby mitigate for dams and their operations) is among the most critical uncertainties for better understanding how to sustain viable salmonid populations. Critical Uncertainty #14 is also a priority because the accuracy of methods used to identify limiting habitat factors at relevant scales is a key to developing accurate relationships between habitat restoration and fish growth and survival.

B. Contributions from Fish and Wildlife Program projects

Overall, few projects have been conducted at the broad spatial scales needed to address CU #13, and none has proceeded long enough to measure the full effects of restoration. In addition, scientists have yet to fully analyze whether the current methods are accurate enough to measure effects across these scales of space and time – a key problem area for addressing CU #14. The CHaMP/ISEMP project is near the cutting edge of research on both critical uncertainties, but many problems remain and much is yet to be done or reported.

Seventeen ongoing Fish and Wildlife Program projects directly addressed CU #13, whereas 12 directly addressed CU #14. Of these, 6 projects simultaneously addressed both. Projects addressed mainly steelhead and Chinook salmon. For example, for CU #13, 10 projects focus on evaluating restoration for steelhead, 7 for Chinook, and 1 each for sockeye, bull trout, Pacific lamprey, and freshwater mussels. Some projects address more than one species, often Chinook and steelhead together.

Projects that address these critical uncertainties are located throughout most subbasins and are designed to collect and analyze data at scales that range from individual stream reaches to entire watersheds. For example, two projects are large, coordinated watershed-scale efforts involving many agencies and using sophisticated experimental designs to address effects of restoring flows, adding large wood, removing barriers, and reconnecting floodplains. The projects are located in one or more subbasins, such as the Tucannon (Proj. 2010-077-00) and the upper Grande Ronde River and Catherine Creek watersheds (Proj. 2009-004-00). However, these two projects have reported on data collected for only 3-4 years each, so only preliminary results are available.

Two large, ongoing projects are making comprehensive, basinwide assessments of these two uncertainties, although the data and analysis reported to date have provided only preliminary results. The Columbia Habitat Monitoring Project (CHaMP, Proj. 2011-006-00) addresses CU #14 by focusing on standard protocols to measure and analyze habitat in wadeable tributaries and methods to analyze these data using a variety of techniques, including hydraulic models, to produce metrics relevant to fish. Methods are being developed in three subbasins using sophisticated sampling designs. The CHaMP program feeds habitat information to the Integrated Status and Effectiveness Monitoring Program (ISEMP, Proj. 2003-017-00). The ISEMP project addresses CU #13 and analyzes relationships between habitat metrics and fish abundance, density, growth, survival, and productivity across spatial scales.

In a recent preliminary review of these two programs, the ISAB/ISRP reported that the creative use of novel modeling approaches to develop useful information for managers sets these programs apart from others, although the details of each program have yet to be evaluated by these science panels. Some of the non-CHAMP/ISEMP projects that directly address these two critical uncertainties are fully integrated with the CHaMP/ISEMP programs, especially those that are part of Intensively Monitored Watersheds (IMWs). In contrast, others do not use these measurement and analysis protocols. A detailed review of CHaMP and ISEMP by the ISRP is planned in the near future, which should inform uncertainties (i.e., CU #13 and #14) and address ways to make progress in the future.

In contrast to these four large-scale comprehensive projects, the others reviewed used only simple before-after designs to measure effects of many different habitat restoration treatments implemented at different times and in a set of relatively short and often scattered reaches within a subbasin. A key weakness for many of these non-CHAMP/ISEMP projects is the lack of quantitative objectives and adequate sampling designs and analysis methods to determine the effectiveness of habitat restoration. Many watersheds have received a variety of restoration treatments, such as flow enhancement, instream structures, riparian plantings, and floodplain reconnection. Often these have been implemented at different times and in overlapping locations and were not strategically integrated at a watershed scale. These factors confound simple "before-after" and "control-impact" monitoring because many watersheds lack measurements of habitat or fish needed to make one or both of these comparisons (for example, sufficient baseline data at both treatment and control sites before any restoration was begun). Likewise, determining the effectiveness of many restoration projects is confounded by changes in releases of hatchery fish during the monitoring period.

Overall, the effectiveness of many habitat restoration actions (e.g., channel complexity and bedform adjustments, riparian forest establishment, large wood inputs) cannot be assessed for 10-100 years because the desired changes occur slowly. Therefore, monitoring of short-term responses may provide a limited or incomplete measure of the long-term success of the intended restoration treatment(s).

Among the projects that potentially address these critical uncertainties, 41 projects address CU #13 and 33 address CU #14. Together this suite of projects makes up around 40% of the approximately 180 projects that contain a research and monitoring work element in the Columbia River Basin. Any of these projects that measure "fish in and fish out" in a subbasin where habitat restoration has been completed or is planned are likely to generate information potentially useful to assess responses to habitat restoration. However, the actual utility of the information depends on adequate data collection, description of conditions before and after project implementation, appropriate analyses, and comparisons of treatment results to appropriate reference conditions. Unfortunately, many projects in this potential category do not collect data suitable for evaluating the effectiveness of habitat restoration.

C. Additional Information

Although much is known about how salmonids use habitat and what habitats they require at scales from meters to kilometers (site and reach scales), relatively little is known about: (a) what set and quality of habitats are needed throughout the entire life cycle of each species, and when and where such habitat conditions are needed; (b) the dominant processes, often occurring at watershed and larger scales, that shape and maintain these sets of habitats; (c) the spatial arrangement of the set of habitats to allow fish to move among them; and (d) the cumulative effects of many different habitat restoration projects throughout watersheds on fish abundance and survival, and how the effects of projects interact with each other and other stressors encountered by fish (Fausch et al. 2002, Roni et al. 2015). This information gap also applies to "resident" fish such as bull trout, which may range up to 100 kilometers throughout their lives rather than thousands of kilometers as for anadromous salmonid species.

At site and reach scales, and over a limited period of time (e.g., one summer), it is challenging, but possible, to determine what factor(s) likely limit fish abundance, survival, and production. Knowledge about what to measure and how to measure it is generally well developed. However, over longer time scales and larger spatial scales that encompass the entire life cycle of a species of salmon or trout, it is unclear how to accurately assess what habitat factors are limiting and how to collect and analyze data that could answer this question. A key reason is that the effects of one factor may depend on another factor (i.e., factors may interact). For example, the effectiveness of tributary habitat restoration for increasing fish productivity to mitigate hydrosystem-related losses may depend on (a) ocean conditions that affect adult growth and survival, and/or (b) the effects of a changing climate on extreme events like floods and droughts that may affect habitat and counteract the recovery produced by restoration actions.

The full importance and influence of watershed condition and trend on the maintenance and/or restoration of riparian and aquatic habitat condition is a major element that has had limited attention in both strategic restoration planning and effectiveness monitoring. Although the need for such a watershed scale perspective is thoroughly discussed in the ISAB Report, ISAB 2011-4, *"Using a Comprehensive Landscape Approach for More Effective Conservation and Restoration,"* techniques for how to evaluate and incorporate these considerations into subbasin planning and project plans are hard to find. Additional research and tools for evaluation and application of watershed condition and trend are needed to achieve more effective and sustainable restoration of aquatic and riparian habitats.

2006 Research Plan Questions 15: What are the impacts of hydrosystem operations on mainstem habitats, including the freshwater tidal realm from Bonneville Dam to the salt wedge? How might hydrosystem operations be altered to recover mainstem habitats?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #15.

A. Progress and Criticality

Progress–Low: Overall, there is much less knowledge and research on the effects of hydrosystem operations on mainstem habitat for salmonids and other focal species, such as Pacific lamprey, white sturgeon, and eulachon, than on factors degrading habitat in tributaries. Only one Fish and Wildlife Program project is addressing this CU, and therefore progress has been low.

Criticality–High: These potential mainstem habitat impacts are considered to be a critical uncertainty because even species that were once thought to rear exclusively in tributaries have been reported to migrate downstream and overwinter, or rear during other seasons, in mainstem habitats.

B. Contributions from Fish and Wildlife Program projects

Only one project addresses this question directly. It is focused on evaluating spawning of fall Chinook and chum salmon below Bonneville Dam and three other dams in the Lower Columbia River (Proj. 1999-003-01). A key research component has been to measure the abundance of threatened chum salmon, and conditions for spawning, incubation, and rearing, along with flows and temperatures. However, to date it appears that no relationships have been developed between spawning or abundance and temperature or flow. These are necessary for predicting suitable future conditions, so much remains to be done.

2006 Research Plan Critical Uncertainty 16: What pattern and amount of habitat protection and restoration is needed to ensure long term viability of fish and wildlife populations in the face of natural environmental variation as well as likely human impacts on habitat in the future?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #16.

A. Progress and Criticality

Progress–Low: Progress on this critical uncertainty has been low because the question is so broad and the responses by fish and wildlife so difficult to quantify at appropriate scales as to make the question largely intractable given the present state of knowledge. Current efforts to restore habitat throughout the Columbia River Basin are a large-scale experiment, but without any replicates or controls that would be necessary to evaluate the outcome. That is, just like evaluating the effects of changing spill on smolt-to-adult survival rates (SAR), there are no control basins the same size and character of the Columbia River where habitat restoration is not being done, nor any replicates of either case.

Criticality–High*:* This is the overarching critical uncertainty for all habitat restoration efforts in tributaries and so is highly critical to the success of the Fish and Wildlife Program.

B. Contributions from Fish and Wildlife Program projects

There is strong overlap among projects that address this critical uncertainty and those that address CU #13 (see above); 7 of 9 projects are the same. Therefore, the summary for CUs #13 and #14 largely applies to this question.

Individual projects that come closest to addressing this uncertainty, at least at the subbasin scale, are planned and carried out over many years and at a large spatial scale. Two projects on spring Chinook salmon described above for CU #13, one on the Tucannon River (Proj. 2010-077-00) and one on the upper Grande Ronde River and Catherine Creek (Proj. 2009-004-00), are the best examples of this scale. However, both projects have been ongoing for only 3-4 years, so results are still preliminary.

The most comprehensive effort that directly addresses this question is the CHaMP-ISEMP project, also described above. This project offers the most hope for achieving a coordinated analysis of habitat restoration at a large scale for various Intensively Monitored Watersheds and other subbasins where conservation and restoration work is being conducted. However, definitive results that could be used to address this critical uncertainty have yet to be produced by this project. A review planned by the Council and the ISRP in the near future will help evaluate how well CU #16 has been addressed to date by this set of projects.

C. Additional Information

The role of upslope and watershed scale conditions and trends, in restoration of stream and riparian habitat, has received limited attention to date. These conditions and trends often reflect processes that occur at larger scales than individual stream reaches but can have a profound impact on the success of aquatic habitat restoration. Techniques for identifying the processes influencing condition and trend and addressing them through improved protection or active restoration at a watershed, or larger, scale are needed. Additionally, effectiveness monitoring of various approaches for addressing watershed condition and trend is needed. A good example of upslope conditions affecting watershed and stream conditions is accelerated erosion and delivery of sediment. Often, this is a major issue identified for treatment in stream restoration, yet it is frequently not evaluated and treated at a watershed scale. In many cases, upslope erosion and sediment delivery to tributary streams, frequently from road systems, is the dominant source of accelerated sedimentation in fish bearing streams.

An additional issue is the lack of research or monitoring, supported by the Program, to evaluate the effectiveness of watershed-scale protection or conservation measures as a restoration tool. This is an important potential tool for meeting restoration objectives since this passive approach can be much cheaper than localized, active restoration and can effectively influence much larger areas. Improved understanding on how to evaluate the strategic use and effectiveness of passive restoration is an important component for the successful restoration of habitat in the Basin.

Estuary

Table 5. Estuary-theme[20] critical uncertainties in the 2006 Research Plan and the number of Fish and Wildlife Program projects that directly or potentially addressed each one.

ID	2006 Research Plan Critical Uncertainty (click on link to see specific projects)	Directly	Potential
17	What is the significance to fish survival, production, and life-history diversities of habitat degradation or restoration in the estuary as compared with impacts to other habitats in the basin? How does this partitioning of effects vary among species and life-history types?	0	6
18	What are the highest priority estuarine habitat types and ecological functions for protection and restoration (e.g., what are most important habitats in the estuary for restoring and maintaining life-history diversities of subyearling Chinook and chum salmon, and how effective were past projects in restoring nursery/feeding areas)?	0	5
19	What specific factors affect survival and migration of species and life-history types of fish through the estuary, and how is the timing of ocean entry related to subsequent survival?	0	11

Progress on uncertainties (#17, #18, and #19) is summarized together rather than individually because none of the Council's funded Fish and Wildlife Program (Program) projects directly addressed these uncertainties.

Summary

The three estuary-theme critical uncertainties arise from the need to evaluate the effects of estuarine habitat restoration projects and to increase understanding of the role of the estuary in the life cycles of fish (Council document 2006-3). The 2006 Plan's general approach to address these questions was the combined monitoring of the physical environment and evaluation of large-scale manipulations of estuarine habitats (ISRP 2003-13, Council document 2006-3). A number of ongoing Fish and Wildlife Program-funded projects indirectly address these uncertainties through potential contribution of data (Table 5). Additional information from programs and projects such as the US Army Corps of Engineers (USACE) Anadromous Fish Evaluation Program (AFEP), the Columbia Estuary Ecosystem Restoration Program (CEERP) (ISAB 2012-6), NOAA Fisheries' Life-Cycle Modeling (ISAB 2013-5), and the Expert Regional Technical Group (ERTG) process (ISAB 2014-1) have contributed to addressing these questions.

Progress on addressing these issues was classified by the ISAB/ISRP as medium and criticality as a priority. Research is needed to quantitatively compare the effects of habitat protection/restoration on

[20] For further background information on the theme, see the 2006 Research Plan summary pages 15 (Estuary) and the 2014 Fish and Wildlife Program strategy for the estuary.

fish (survival, production, life history diversity) in estuary, mainstem, and tributary habitats in order to evaluate the effectiveness of past protection/restoration efforts and to determine the highest priority habitats for future protection/restoration efforts.

Overview of Ongoing Projects and Additional Information Addressing the Questions

See Table of FY 2015 projects addressing CU #17**,** CU #18 and CU #19.

A. Progress and Criticality

Progress–Medium: Progress on addressing questions for parts of the estuary theme was made primarily by projects funded outside of the Council's Fish and Wildlife Program. This was accomplished by projects that identified priority estuarine habitats for restoration, ecological functions, and other factors potentially significant to salmonid survival, production, and life-history diversity (*see* section C). To our knowledge, no projects have quantitatively compared the effects of estuarine habitat degradation or restoration on fish survival, production, and life-history diversities with those in other habitats in the Basin.

Criticality–Priority: Research to identify and quantify the factors affecting estuarine survival of fish and responses of fish to alternative restoration actions and locations throughout the Basin is considered essential to achieving Fish and Wildlife Program goals to enhance conditions for salmon and steelhead in the estuary and to improve and expand habitat function, structure, complexity, and range of aquatic habitats.

B. Contributions from Fish and Wildlife Program Projects

While a number of Fish and Wildlife Program projects potentially address the three uncertainties through collection of relevant information, the ISAB identified some important data gaps. For example, if a life-cycle modeling approach is used to address these uncertainties, then the most important data gap is the lack of defining/understanding functional relationships showing how changes (degradation or restoration) in habitat quantity and quality affect fish survival, production, and life-history diversity. In addition, the scale of data collection is presently insufficient throughout the Basin to address relative benefits of restoration by life stage and habitat. For approaches using comparative statistical analyses and partitioning of effects, metrics need to be consistent across all habitats in the Basin. Metrics currently differ by habitat, e.g., productivity and survival rates in the tributaries; presence/absence, growth, and residence time in the estuary (Johnson et al. 2012). A key data gap is the lack of knowledge about survival rates of fish in the estuary at all life stages, notwithstanding some additional information specific to survival of salmonid smolts (see section C). The ISAB considers that restoration activities should address all focal fish species (anadromous salmonids, sturgeon, eulachon, and Pacific lamprey) and life stages.

C. Additional Information

Most research pertaining to estuary-theme questions is conducted by projects funded outside of the Council's Fish and Wildlife Program. Here, we briefly summarize information from some of the programs and projects in the Basin that can be used to begin addressing the 2006 Research Plan's estuary-theme questions. We do not review information from programs and projects conducted in estuaries external to the Columbia River Basin.

The Columbia Estuary Ecosystem Restoration Program (CEERP) is the collective habitat restoration and research, monitoring, and evaluation (RME) effort in the Lower Columbia River Estuary (LCRE) conducted by BPA, USACE, and others to direct implementation of estuary actions in the Federal Columbia River Power System Biological Opinion (FCRPS BiOp) under the Endangered Species Act (BPA/Corps 2012). The Council's Program incorporates estuary actions in the BiOp as general measures, but the estuary sub-strategy in the Program is broader than the Endangered Species Act in terms of both fish and wildlife species considered and objectives (Council Document 2014-12). One of CEERP's most important uncertainties is evidence, direct or indirect, of the effects of estuarine habitat restoration on juvenile salmon survival in the estuary or other measures, such as growth, condition, and returns of adult salmon. At present, information to evaluate this uncertainty is produced by an expert panel (called the Expert Regional Technical Group, ERTG) that calculates "Survival Benefit Units," an index intended to represent the effect of LCRE habitat restoration projects on juvenile salmon survival (ISAB 2014-1). The BPA and USACE have committed to specific targets for improved survival of juvenile salmon under the 2008 FCRPS BiOp—49 survival benefit units for ocean-type (sub-yearling) salmon and 30 survival benefit units for stream-type (yearling) salmon by 2018. However, an ISAB review of the process, used by ERTG, to calculate survival benefit units concluded that the "capability of [habitat restoration] projects to actually succeed in increasing the survival of salmon through their residence and migration in the Columbia River estuary cannot be determined from the Scoring Criteria" used by ERTG to calculate survival benefit units (ISAB 2014-1). Previous ISAB advice from the CEERP review (ISAB 2012-6) is still relevant: *"A highly focused RME approach that estimates stock-specific survival rates in all major habitat types in the estuary and identifies habitats/locations where there are survival bottlenecks for species and stocks that migrate through Federal Columbia River Power System (FCRPS) is needed. Once these estuary bottlenecks are identified, it will be much easier to determine the most cost-effective approaches to habitat restoration that will be of benefit to Columbia River fish and wildlife."*

The Cumulative Effects project, conducted by USACE and Pacific Northwest National Laboratory in 2004-2010, defined cumulative restoration effects (CE) as "the net change in ecosystem-wide metrics and ecosystem state resulting from cumulative restoration impacts" (Johnson et al. 2012). The project produced: "(1) effectiveness monitoring protocols and methods to standardize monitoring activities; (2) the theoretical and empirical basis for a CE methodology using a levels-of-evidence approach; (3) evaluations using ecological relationships, geo-referenced data, hydrodynamic modeling, and meta-analyses; and (4) an adaptive management process to coordinate and coalesce restoration efforts in the LCRE" (Johnson et al. 2012). However, at the completion of this project, investigators concluded that more data about the mechanisms linking restoration of LCRE ecosystems to effects on juvenile salmonids were needed.

An ongoing, multi-year study (2011-2018) conducted by USACE/AFEP and the Pacific Northwest National Laboratory is addressing the ecological benefits of restoration actions at multiple spatial scales in the estuary (site, landscape, and estuary-wide scales) over time (Johnson et al. 2013). At the estuary scale, the project has produced a compendium of tag release-recapture statistical designs that can be used to assess salmon performance in the lower Columbia River estuary.

Since 2005, a number of related studies conducted by USACE/AFEP, NOAA/NWFSC, Pacific Northwest National Laboratory, and others have used acoustic tags (i.e., the USACE-developed Juvenile Salmon Acoustic Telemetry System [JSATS]) and PIT tags to estimate smolt survival through the estuary. Results have documented smolt migration pathways, associated travel times, and reach-specific survival probabilities (Harnish et al. 2012). However, because of size constraints, PIT and acoustic tags currently cannot be used to estimate estuarine survival of fry and presmolts that rear in the estuary, nor smolts less than about 90 mm (3.5 inches) in fork length (Brown et al. 2013). These studies were terminated due to high costs.

Another ongoing project conducted by USACE/AFEP and Pacific Northwest National Laboratory (Evaluation of Life History Diversity, Habitat Connectivity, and Survival Benefits Associated with Habitat Restoration Actions in the Lower Columbia River and Estuary) is developing a geospatial, web-accessible database called “Onchor” for action effectiveness and related data from monitoring and research efforts that can be synthesized and evaluated to support CEERP and its ecosystem restoration mission in the LCRE (Coleman et al. 2013).

The influence of restoration activities on the recovery and viability of ESA-listed salmonids is a major focus of NOAA Fisheries’ ongoing life-cycle modeling efforts. At present, avian predation is the only functional relationship incorporated into the estuary model.[21] The model indicates that a 50% reduction in avian predation (assuming no compensatory mortality, for example, from disease or other predators) would lead to increases in estuarine survival of 1.7% for Chinook and 11.5% for steelhead. Investigators intend to address estuarine habitat restoration and predation by pinnipeds in future iterations of the model. In a review of this modeling effort, the ISAB concluded that life-cycle modeling is a better scientific approach than using an expert panel process such as ERTG to address uncertainties related to the influence of restoration activities on anadromous salmonid recovery and viability (ISAB 2013-5).

Published studies by NOAA scientists investigated the importance of size, timing, and survival at ocean entrance. Statistical analyses of data from over 40,000 tagged Snake River Basin Chinook and steelhead indicated the importance of date of arrival in the estuary; that is, smolt-to-adult survival of juveniles of both species migrating from early to mid-May was 4–50 times greater than those migrating in mid-June (Scheuerell et al. 2009). In addition, estimated peak survivals varied by ocean entrance year, indicating the influence of interannual variation in ocean conditions on SARs. Weitkamp et al. (2015) demonstrated that timing of ocean entrance of Columbia River Basin salmon and steelhead is stock-specific and related to early ocean growth and potentially to survival.

[21] http://www.nwfsc.noaa.gov/trt/lcm/docs/Interior.Columbia.LCM.6.28.13.pdf

Ocean

Table 6. Ocean-theme[22] critical uncertainties in the 2006 Research Plan and the number of Fish and Wildlife Program projects that directly or potentially addressed each one.

ID	2006 Research Plan Critical Uncertainty (click to see table of specific projects)	Directly	Potential
20	Can stock-specific data on ocean abundance, distribution, density-dependent growth and survival, and migration of salmonids, both hatchery and wild, be used to evaluate and adjust marine fishery interceptions, harvest, and hatchery production in order to optimize harvests and ecological benefits within the Columbia River Basin?	2	0
21	Can monitoring of ocean conditions and abundance of salmon and steelhead during their first weeks or months at sea improve our ability to predict interannual fluctuations in the production of Columbia Basin Evolutionarily Significant Units (ESUs) or populations to enable appropriate changes to harvest levels?	2	0
22	How can interannual and interdecadal changes in ocean conditions be incorporated into management decisions relating to hydrosystem operations, the numbers and timing of hatchery releases, and harvest levels to enhance survival rates, diversity, and viability of ESA-listed salmonids?	2	0
23	What are the effects of commercial and sport fishing on ocean food webs?	0	0

Progress on critical uncertainties #20, #21, and #22 is summarized together rather than individually because the two ocean-theme Program projects address them as a set, i.e., the Ocean Survival of Salmonids (NOAA) and the Canada-USA Shelf Salmon Survival Study (Canada Department of Fisheries and Oceans). To our knowledge, no projects directly or potentially address critical uncertainty #23.

Overview of Ongoing Projects Addressing the Question and Additional Information

See Tables of FY 2015 projects addressing CU #20, CU # 21, CU #22 and CU #23.

A. Progress and Criticality

Progress–High: The two ongoing ocean-theme projects made considerable progress in determining stock-specific life history traits and monitoring ocean conditions that potentially affect growth and survival of salmonids during the early marine stage. Qualitative forecasts of the effects of ocean conditions on adult salmon returns were developed. The Council's Ocean and Plume Science

[22] For further background information on the theme, see the 2006 Research Plan summary (page 16) and the 2014 Fish and Wildlife Program strategy for the plume and ocean.

Management Forum intends to identify potential management implications of ocean research and priorities for future ocean research.

Criticality–High*:* Ocean-theme research questions are highly critical to the Council's Fish and Wildlife Program because unexplained variation in survival of the Basin's anadromous fish species is highest for ocean life stages.

B. Contributions from Fish and Wildlife Program Projects

Two 2015 projects directly address uncertainties #20, #21, and #22, NOAA's Ocean Survival of Salmonids study, which began in 1998, and Fisheries and Oceans Canada's Canada-USA Salmon Shelf Survival study, which began in 1999. Both projects have demonstrated the feasibility of using research vessels to conduct ecosystem surveys that simultaneously monitor ocean conditions and the status of juvenile salmonids along coastal migration corridors from Oregon to Southeastern Alaska. The projects collect stock-specific data (primarily through genetics and coded wire tags [CWTs]) on salmonids. The results have shown when and where species, ESUs, and stock groups of Columbia River Basin salmonids are found in the estuary, plume, and nearshore coastal habitats. The data have been used to test hypotheses about variation in abundance, distribution, growth, density-dependent (hatchery-wild) interactions, and survival and their relationships to ocean conditions. Overall, the results have improved scientific understanding of stock-specific responses of Columbia River salmonids to variable ocean conditions. However, a review by the ISRP in 2012 concluded that stronger linkages between marine ecological processes and salmon survival estimates are needed (ISRP 2012-3). The lack of survival estimates for the early marine life-stage is a major data gap. For example, ocean survival is often measured as the ratio of smolts emigrating to adults counted at Bonneville Dam (or other dams) and is not portioned to any finer spatial resolution.

Currently, the NOAA project uses a number of physical, biological, and ecosystem indicators to specifically define the term "ocean conditions," and these metrics can be used to provide a qualitative forecast of the survival of salmon 1-2 years in advance.[23] For example, the ocean conditions metrics indicate "juvenile salmon entering the ocean in 2014 encountered below average ocean conditions off Oregon and Washington likely leading to below average returns of adult coho salmon in 2015 and Chinook salmon in 2016." NOAA's forecast of below average returns of adult coho salmon in 2015 has been confirmed by 2015 counts at Bonneville Dam. Information sharing, dialogue and collaboration between ocean and plume researchers and estuary and freshwater managers in the Council's Ocean and Plume Science Management Forum are aimed at identifying management applications of ocean and plume data, including harvest impacts on the Columbia River Basin ecosystem.

C. Additional Information

Ocean research and monitoring programs and projects conducted outside of the Council's Fish and Wildlife Program have collected substantial information that could potentially be used to at least partially address 2006 ocean-theme questions. For example, the North Pacific Anadromous Fish

[23] http://www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/g-forecast.cfm

Commission's 2011-2015 science plan is focused on explaining and forecasting the annual variation in Pacific salmon production under changing climate and ocean conditions, including research on early ocean migration and survival mechanisms (http://www.npafc.org). The North Pacific Marine Science Organization (PICES) (http://www.pices.int/) collaborates with NPAFC and periodically reviews and summarizes the status and trends of the marine ecosystems in the North Pacific, including the California Current Ecosystem, and considers the factors that are causing or are expected to cause change in marine ecosystems in the near future. The North Pacific Research Board (NPRB) supports peer-reviewed scientific research in the Gulf of Alaska and other regions that informs effective management and sustainable use of marine resources. However, relevant data and results from these and other marine research programs and projects need to be identified, synthesized, and analyzed, and additional information needs to be collected to specifically address the 2006 ocean-theme questions.

Harvest

Table 7. Harvest-theme critical uncertainties in the 2006 Research Plan and the number of Fish and Wildlife Program projects that directly or potentially addressed each one.

ID	2006 Research Plan Critical Uncertainty (click to see table of specific projects)	Directly	Potential
24	What are the effects of fishery interceptions and harvest in mixed-stock areas, such as the ocean and mainstem Columbia, on the abundance, productivity, and viability of ESUs or populations, and how can fishery interceptions and harvests of ESUs or populations, both hatchery and wild, best be managed to minimize the effects of harvest on the abundance, productivity, and viability of those ESUs and populations?	4	13
25	What new harvest and escapement strategies can be employed to improve harvest opportunities and ecological benefits within the Columbia Basin while minimizing negative effects on ESUs or populations of concern? Can genetic techniques be used to quantify impacts on wild or ESA-listed stocks in ocean fisheries?	4	6
26	How can the multiple ecological benefits that salmon provide to the watersheds where they spawn (e.g., provision of a food resource for wildlife and a nutrient source for streams and riparian areas) be incorporated effectively into procedures for establishing escapement goals?	0	4

Summary

The 2006 Research Plan stated that *"Harvest management for many fish populations in the Columbia River Basin has substantially changed due to state and federal listings. Harvest for listed populations is managed under biological opinions that attempt to ensure fisheries do not pose jeopardy to listed fish species. Most current harvest management targets fish from mitigation hatcheries; productivity to support harvest has been largely divorced from production in natural habitat.*

The ISAB Harvest Management Review (ISAB 2005-4) addressed the question: what constitutes a sound scientific basis for the management of Pacific salmonids in the Columbia River Basin? The report also noted critical uncertainties as to the effect of harvest on the conservation of naturally produced salmonids, including the fundamental need to better monitor and understand mixed-stock fisheries. Three fundamental components of harvest management were identified as causes of concern: a paucity of quantitative data for analyses by population units; limited identification and assessment of the catches of hatchery and wild stocks to identify trends in their status and provide a biological basis for production goals; and limited evidence of accounting for uncertainty in management plans."

Some progress has been made on the 2006 harvest uncertainties, as briefly listed below, but much more effort is needed to address fully these important questions. Expanded effort to address the questions could lead to greater harvests of hatchery fish and greater viability of natural populations, which are two key goals of the Fish and Wildlife Program. For example:

- Off-channel Select Area Fishery Enhancement (SAFE) in the lower Columbia River and the Colville Tribes' mark-selective fishery in the upper Columbia River represent advances for increasing harvests of hatchery salmon while reducing potentially adverse harvest, genetic, and ecological-related effects on natural populations.

- Columbia River Inter-Tribal Fish Commission (CRITFC) and Idaho Department of Fish and Game (IDFG) are developing parentage based tagging and genetic stock identification approaches for estimating hatchery- and natural-origin salmonids in fisheries. This approach could be expanded to ocean fisheries and to more areas in the Basin to improve monitoring of natural populations.

- Fisheries management actively avoids jeopardy of ESA-listed stocks, but more effort is needed to develop biologically based goals for spawning populations as a means to evaluate current capacity to support natural salmonids, manage spawning populations, and to gain ecosystem benefits from spawning salmon.

2006 Critical Uncertainty 24: What are the effects of fishery interceptions and harvest in mixed-stock areas, such as the ocean and mainstem Columbia, on the abundance, productivity, and viability of ESUs or populations, and how can fishery interceptions and harvests of ESUs or populations, both hatchery and wild, best be managed to minimize the effects of harvest on the abundance, productivity, and viability of those ESUs and populations?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #24.

A. Progress and Criticality

Progress–Medium: Fisheries are managed in part to avoid jeopardy of the ESA-listed populations (or ESUs) while attempting to target more abundant and productive populations. Minimum abundance spawning thresholds (MAT) have been developed for some ESA-listed populations, but such estimates are not based on stock recruitment relationships that identify current capacity (Interior Columbia Basin Technical Recovery Team 2007).

Criticality–Priority: More effort is needed to evaluate fully the effects of harvest on stock recruitment dynamics, to better estimate current population carrying capacity, and to efficiently harvest surplus hatchery fish. Biologically based spawning goals, including pHOS targets, should be developed, justified in reports, and targeted by fishery managers. This information could lead to more robust natural populations and harvests.

B. Contributions from Fish and Wildlife Program Projects

Two Fish and Wildlife Program projects partially address the question: *"What are the effects of fishery interceptions and harvest in mixed-stock areas, such as the ocean and mainstem Columbia, on the abundance, productivity, and viability of ESUs or populations."* The Deschutes River fall Chinook population (Ann. Proj. Rept. 2008-306-00) is an indicator stock for the Pacific Salmon Commission and tagging information from this project is used to set harvest rates in mixed-stock coastal fisheries to sustainably manage other fall Chinook populations. The Okanogan and Wenatchee sockeye project (Ann. Proj. Rept. 2008-503-00) examines sockeye survival and abundance, including the magnitude of fishery interceptions in the mainstem.

Two Program projects address the question, *"How can fishery interceptions and harvests of ESUs or populations, both hatchery and wild, best be managed to minimize the effects of harvest on the abundance, productivity, and viability of those ESUs and populations?"* They are the SAFE project (Ann. Proj. Rept. 1993-060-00) in the lower Columbia River and the Colville Tribes' mark-selective fishery (Ann. Proj. Rept. 2008-105-00) in the upper Columbia River. These two projects have the potential for broad application in the Basin to increase harvests of hatchery fish while also promoting the viability of natural populations.

Thirteen Program projects potentially support the evaluation of harvest effects on fish populations. These projects include several coded-wire-tag (CWT) and genetic stock identification projects. In particular, projects 2008-907-00 and 2010-031-00 involve development of new parentage based tagging approaches that along with other more routine genetic stock identification tools will likely lead to improved identification of hatchery and natural-origin salmon stocks in mixed-stock fisheries. These data can be used in an effects analysis. Until then, coded-wire-tag (CWT) efforts (funded in part by the Program) are used to estimate stock composition in fisheries. Most CWTs are applied to hatchery fish, and an uncertainty is the degree to which the tagged hatchery fish represent associated natural-origin salmon.

C. Additional Information

Harvests of ESA-listed populations are managed by government agencies under consultations and biological opinions that attempt to ensure fisheries do not pose jeopardy to listed fish species. The quantitative effects of fisheries on population viability, however, are largely limited to estimating harvest rates and avoiding jeopardy. For the most part, fishery management does not address questions such as: To what extent did the fishery prevent the natural population or ESU from reaching the spawning level that would provide the potential for maximizing adult abundance in subsequent generations? New stock recruitment analyses have been conducted and some biologically based spawning escapement goals have been developed. The *US versus Oregon* (2008) management agreement directs the Technical Advisory Committee to develop escapement goals for upriver stocks. However, much more work is needed to describe salmonid recruitment curves and develop biologically based spawning escapement goals, especially in light of recent findings showing surplus hatchery fish on spawning grounds (see ISAB 2015-1, ISAB 2005-4). Development of spawning goals should be documented in reports. Harvest managers recognize the need to improve habitat conditions to increase population productivity and capacity, but this should not constrain development of biologically based recruitment curves that reflect current conditions. Recruitment curves and biologically based escapement goals could lead to more robust natural populations and harvests.

2006 Critical Uncertainty 25: What new harvest and escapement strategies can be employed to improve harvest opportunities and ecological benefits within the Columbia Basin while minimizing negative effects on ESUs or populations of concern? Can genetic techniques be used to quantify impacts on wild or ESA-listed stocks in ocean fisheries?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #25.

A. Progress and Criticality

Progress–Medium: Recent evidence indicates there are many surplus hatchery fish on the spawning grounds that could be harvested for the benefit of both fishers and natural salmonid populations (ISAB 2015-1). Two Fish and Wildlife Program projects demonstrate strategies to increase harvests of hatchery fish while minimizing impacts on natural fish, but additional effort and development of the strategies are needed. The combination of parentage based tagging plus genetic stock identification is a new approach that can be used to estimate more accurately stock-specific harvests of wild salmon, but the approach needs to be expanded to incorporate more stocks and fisheries in the Basin and along the coast.

Criticality–Priority: This was judged to be a “Priority” uncertainty because key goals of the Program are to mitigate for lost harvest opportunities and to increase native fish productivity and abundance.

B. Contributions from Fish and Wildlife Program Projects

The selective fishery project by the Colville Confederated Tribes (Ann. Proj. Rept. 2008-105-00) directly addressed this uncertainty by (1) reducing density dependence and introgression associated with hatchery fish spawning in streams, and (2) enabling harvests by tribal members while minimizing negative impacts of natural populations. The Colville project identified several key selective gears (purse seine, weir, and beach seine) that could be used to selectively harvest hatchery origin fish. Additional work, however, is needed to further evaluate catch and release mortality of natural salmonids. The project findings have broad applicability in the Basin if other fishing groups can be encouraged to use selective fishing techniques in terminal areas to harvest hatchery fish that exceed the capacity of the watershed to support them.

Removal of Powerdale Dam has enabled Hood River steelhead and spring Chinook populations to increase. The Hood River M&E project (Ann. Proj. Rept. 1988-053-04) is monitoring these populations and tracking fishery harvests that were enabled by dam removal.

The CRITFC and IDFG projects (Ann. Proj. Repts. 2008-907-00, 2010-031-00) are directly addressing the second question: *"Can genetic techniques be used to quantify impacts on wild or ESA-listed stocks in ocean fisheries?"* The projects are developing the parentage based tagging and genetic stock identification approaches for use in estimating hatchery- and natural-origin salmonids in fisheries. Expansion of the parentage based tagging/genetic stock identification (PBT/GSI) analyses to other parts of the Basin and to ocean fisheries is needed.

Six projects involve harvest and population monitoring. These efforts potentially support the question, *"What new harvest and escapement strategies can be employed to improve harvest opportunities and ecological benefits within the Columbia Basin while minimizing negative effects on ESUs or populations of concern?"* Ultimately, monitoring and evaluation are needed to develop stock-recruitment curves and biologically based spawning goals for the populations. These projects provide information, but additional analyses are needed to address the question.

C. Additional Information

The ISAB (2015-1) provides evidence for the benefits to fishers and to natural populations associated with harvesting surplus hatchery fish. Selective fishing approaches are becoming more common in other regions (British Columbia, West Coast of the USA) and in the Columbia Basin (e.g., removal of surplus hatchery Chinook in Tumwater Canyon, Wenatchee River; Ann. Proj. Rept. 2003-039-00). In the lower mainstem of the Columbia River, purse seine and beach seine gears are being tested as a means to harvest hatchery Chinook and coho while releasing steelhead.[24] Although new parentage based tagging coupled with genetic stock identification hold promise to improve stock identification in ocean and river mixed-stock fisheries, a more coordinated effort and expanded program development are needed. This approach is under investigation by the Pacific Salmon Commission and other entities.

2006 Critical Uncertainty 26: How can the multiple ecological benefits that salmon provide to the watersheds where they spawn (e.g., provision of a food resource for wildlife and a nutrient source for streams and riparian areas) be incorporated effectively into procedures for establishing escapement goals?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #26.

A. Progress and Criticality

Progress–Medium: General principles and results are known, but site-specific results for large stock complexes are not known well. As noted previously, there is a need to develop biologically based

[24] http://www.dfw.state.or.us/fish/OSCRP/CRM/action_notes.asp

spawning escapement goals. Ecological benefits of spawning salmon are an important consideration in the development of biological goals.

Criticality–Medium: Given the observation that total spawner abundances exceed current carrying capacity in some watersheds (ISAB 2015-1), an important question is: Can spawning hatchery fish in excess of current production capacity lead to increased production capacity in the future? Alternatively, is it better to harvest surplus hatchery fish, reduce the percentage of hatchery fish on the spawning grounds (pHOS), and enable the potential for natural-origin fish to adapt to the local environment? If nutrient addition is found to be key to restoring salmon production (increasing capacity), could this be done with carcass analogs or distribution of hatchery carcasses rather than allowing surplus hatchery fish to interbreed with natural-origin salmon? These questions have not yet been tested experimentally.

B. Contributions from Fish and Wildlife Program Projects

None of the Program projects directly addressed this uncertainty. However, the ongoing Salmon River Basin Nutrient Enhancement study (Ann. Proj. Rept. 2008-904-00) potentially addresses this question by experimentally enriching nutrient limited upper Salmon River Subbasin streams with carbon, nitrogen, and phosphorus from salmon carcass analogs (SCA). Salmon analogs have been examined in a number of Columbia Basin streams via efforts funded by BPA (reviewed by Kohler et al. 2012). The review study concluded that carcass analogs have the potential to increase the productivity of nutrient-limited freshwater ecosystems and may provide a nutrient mitigation tool in ecosystems where marine derived nutrients (MDNs) are severely limited or unavailable. However, the ecosystem may respond differently to analogs than to salmon carcasses. Nutrients from carcasses or analogs have not been directly considered when developing spawning escapement goals.

C. Additional Information

Studies show the benefits of salmon carcasses to progeny growth, other fishes, wildlife, and riparian vegetation; potential benefits to salmon survival are assumed from greater growth (e.g., Naiman et al. 2002, ISAB 2011-1 and ISAB 2015-1 and references within) and habitat eventually developed from riparian inputs. A recent study in the Columbia Basin, partially funded by BPA, revealed a net export of nutrients from the Idaho watersheds when spawning densities were low (Kohler et al. 2013). Studies also show detrimental effects such as bio-transport of pollutants from the ocean to freshwater and terrestrial food webs (ISAB 2011-1). From a stock-recruitment perspective, spawning escapements could be managed to enable the potential for maximum adult returns (using stock recruitment relationships) as a means to provide the potential for relatively consistent benefits for fish, wildlife, and riparian vegetation.

It is currently uncertain whether periodic, high spawning abundances (beyond carrying capacity) are needed to maintain or increase population capacity. An emerging issue is whether continuous large spawning escapements of hatchery origin salmon (and/or carcass analogs) can lead to greater carrying capacity in the future, or if surplus hatchery fish should be harvested as a means to reduce strong density dependence and enable the potential for local adaptations by natural salmonids (ISAB 2015-1, HSRG 2015).

Population Structure and Diversity

Table 8. Population structure and diversity theme[25] critical uncertainties in the 2006 Research Plan and the number of Fish and Wildlife Program projects that directly or potentially addressed each one.

ID	2006 Research Plan Critical Uncertainty (click to see table of specific projects)	Directly	Potential
27	What approaches to population recovery and habitat restoration are most effective in regaining meta-population structure and diversity that will increase viability of fish and wildlife in the Columbia River Basin?	3	9
28	How do artificial production and supplementation impact the maintenance or restoration of an ecologically functional metapopulation structure?	6	14
29	What is the relationship between genetic diversity and ecological and evolutionary performance, and to what extent does the loss of stock diversity reduce the fitness, and hence survival rate and resilience, of remaining populations?	2	19
30	What are the differential effects of flow augmentation, transportation, and summer spill on “ocean type vs. reservoir type” fall Chinook?	3	4

Summary

Fish and wildlife populations are characterized by genetic and phenotypic diversity in physiology, behavior, life history, and ecological interactions, which buffers populations against short- and long-term environmental variation. In anadromous salmonids, diversity among populations has been lost through the extinction of locally adapted populations, and diversity within populations has been lost through reductions in the distribution and abundance of many remaining populations. Loss of genetic diversity is expected to compromise the productivity and adaptability of individual populations, as well as the aggregate production and resilience of partially connected populations (a metapopulation), or collection of isolated populations. A better understanding is needed of the dominant processes influencing the distribution and interconnection of populations, and the renewal and maintenance of diversity through time and space.

Additionally, a demographically isolated population is the fundamental unit of viability analysis. Effectively evaluating the status of a species may depend on correctly understanding its population structure – how diversity is distributed among populations of the species. Identification of strong, weak, and at-risk native populations is a critical step in determining actions to preserve and protect populations. Some species have co-occurring life-history types (e.g., resident versus anadromous rainbow trout, ocean versus reservoir type fall Chinook) which can differ in their habitat requirements

[25] For additional background information on this theme, see the 2006 Research Plan summary, page 18.

and productivity. These differences can pose challenges for habitat restoration or harvest management.

2006 Critical Uncertainty 27: What approaches to population recovery and habitat restoration are most effective in regaining meta-population structure and diversity that will increase viability of fish and wildlife in the Columbia River Basin?

Overview of Ongoing Projects Addressing the Question and Additional Information

See [Table of FY 2015 projects addressing CU #27].

Note: Projects that focus on artificial propagation as an approach to recovering metapopulation structure and diversity are considered separately under CU #28.

A. Progress and Criticality

Progress–Low: Considerable theoretical knowledge and practical experience exist for some species groups, but in general, the long-term effectiveness of such actions to increase the viability of fish and wildlife remains poorly understood.

Criticality–High: This question focuses on an important aspect of recovery, is consistent with a landscape approach, and points to practical strategies for improving current activities.

B. Contributions from Fish and Wildlife Program projects

Three projects are directly addressing some parts of CU #27. Two projects are providing detailed maps of the annual distribution and abundance of anadromous salmon within subbasins with very different characteristics. Project 1999-020-00 is in the Middle Fork Salmon River which provides favorable temperature and flow in relatively pristine habitat, whereas Project 2003-022-00 is in the Okanagan subbasin which is hot, dry and intensively modified by logging and agriculture. These studies will document spatial and temporal patterns in extinction and colonization and could help to assess how spatial structure, population connectivity, and synchrony are influenced by management approaches including supplementation, habitat restoration, and other changes in the landscape.

Another project (Ann. Proj. Rept. 2008-504-00) is investigating, in part, how the viability of white sturgeon populations might be affected by the observed lack of sturgeon movement among reservoirs. Genetic differences have been detected among putative stocks of white sturgeon partially isolated by dams, but it remains unclear whether these differences indicate historical biologically meaningful adaptations to specific areas or are a consequence of recent artificial isolation.

No project by itself is capable of fully addressing CU #27. More integration and/or expansion of projects to explicitly link monitoring and experimental components are needed to make progress. In particular, long-term studies are needed to evaluate how changes in connectivity and population sizes relate to habitat restoration activities, perhaps by using predictions from the CHaMP/ISEMP projects.

Nine projects were classified as potential, because their findings have not yet been synthesized or analyzed in a way that could contribute to resolving this uncertainty. However, two closely integrated projects – CHaMP (Proj. 2011-006-00) and ISEMP (Proj. 2003-017-00) – come close to addressing this uncertainty by developing and testing models to determine what habitat factors limit salmon recovery in three main subbasins. Although metapopulation structure has not yet been considered explicitly, empirical fish-habitat relationships are being developed from mapped geomorphic and other data that allow spatially explicit estimates of survival and productivity (e.g., smolts/spawner) over subbasins, and eventually larger areas. The goal is to predict population productivity from habitat data more generally, so it may be useful to link these analyses to genetic diversity and to evaluate connectivity. The complexity of these relationships will ultimately limit predictability, but the CHaMP/ISEMP approach appears promising and is the most comprehensive effort to date.

Four projects related to habitat restoration actions are monitoring responses in population status, productivity, genetic diversity and/or movements following changes to habitat. These projects vary widely in spatial scale and span a variety of species including both non-salmonid fishes (white sturgeon, Pacific lamprey, bull trout) and wildlife (small mammals, birds, amphibians).

Three site-specific monitoring projects provide baseline data on the distribution and status of natural spawning populations of winter steelhead in the Mid-Columbia River Basin and spring Chinook, summer steelhead and bull trout in the lower Deschutes River Basin. These projects could potentially contribute to resolving uncertainties involving productivity, carrying capacity and spatial diversity of fish populations, but would require comprehensive meta-analysis to understand the relationships among individual populations.

C. Additional Information

NOAA Fisheries is developing a metapopulation framework for life-cycle modeling (reviewed in ISAB 2013-5). Two goals in the 2009 FCRPS AMIP were to (1) develop metapopulation models that can identify populations at risk of extinction owing to isolation and (2) analyze temporal concordance among populations arrayed across space. Accordingly, research to date has focused on examining patterns of isolation among Snake River spring/summer Chinook salmon populations to identify population “sources and sinks” and spatial correlations in Chinook population abundance in the upper Columbia and Snake rivers.

2006 Critical Uncertainty 28: How do artificial production and supplementation impact the maintenance or restoration of an ecologically functional metapopulation structure?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #28.

A. Progress and Criticality

Progress–Medium: Considerable empirical and theoretical information now exists about short-term impacts, both positive and negative, but little is known about the long-term consequences of these actions.

Criticality–Medium: An ecologically functional metapopulation implies long-term sustainability through natural reproduction and resilience to environmental variation. To achieve this result, supplementation should be integrated with habitat restoration to maintain natural reproduction and connectivity among spawning areas.

B. Contributions from Fish and Wildlife Program projects

Six projects are directly addressing some parts of CU #28. Two projects are investigating the effectiveness of hatchery reforms aimed at maintaining genetic diversity, a more natural regime for growth and age at smolting in juveniles, and better adapted (local) broodstock for spring Chinook and steelhead supplementation.

Three other projects are tracking the success of efforts to reintroduce Pacific salmon populations by artificial propagation. In project 1988-053-03, hatchery spring Chinook smolts were reintroduced to the Hood River and annual surveys have been conducted to determine which spawning areas are being used, and to identify the possible creation of partially isolated spawning populations. More consideration of how recolonization patterns are affected by release location, timing of release and number of fish released would be useful. Project 2000-039-00 is designed to also assess habitat and watershed restoration efforts in the Walla Walla Subbasin by collaboratively monitoring trends in the abundance, productivity, diversity, and spatial distribution of hatchery vs. wild salmon in the Walla Walla River basin, with focus on spring Chinook, steelhead, and bull trout. Overall, the reintroduction effort is considered successful as the Chinook population has been increasing, but the habitat is not yet fully seeded, perhaps due to factors outside the basin, in the mainstem, estuary, and/or ocean. Project 2009-009-00 is assessing a number of efforts to establish new natural populations of Chinook and sockeye salmon by stocking out-of-basin hatchery- or natural-origin fish into subbasins where indigenous populations have been extirpated. Genetic analyses are being conducted in two streams to ascertain the relative reproductive success (RRS) of hatchery-origin fish, and to determine whether hatchery-origin fish reintroduced into habitat where natural-origin fish have been extirpated are adapting to their new habitats.

Another project (2008-504-00) is investigating in part how the viability of white sturgeon populations might be affected by restricted gene flow among reservoirs, but it is unclear how results from this study will guide decisions at white sturgeon hatcheries. Genetic differences have been detected among putative stocks of white sturgeon partially isolated by dams, but it remains unclear whether these differences indicate historical, biologically meaningful adaptations to specific areas, or are a consequence of recent artificial isolation.

Fourteen projects indirectly address CU #28, at least in part, in that they are tracking the spatial and temporal distribution of natural and hatchery origin spawners following supplementation. Some are attempting to reintroduce extirpated stocks and to test methods for **promoting genetic adaptation to local conditions.** Many are using sophisticated genetic methods to investigate interactions between hatchery origin and natural-origin Chinook, and to measure straying or relative reproductive success. The landscape genetics approach adopted in Project 2009-005-00 appears to have great potential for addressing uncertainties related to genetic diversity, metapopulation structure, local adaptation, and resilience to climate change; for example, the experimental study of redband trout lineages indicates differential expression of heat shock and other genes that may be important for evolution of thermal tolerance. Collectively, these findings could help to understand how hatchery supplementation might be designed to maintain or regain metapopulation structure and diversity.

Three other projects are developing and using genetic monitoring techniques in combination with physical tagging at various life stages, and field and hatchery sampling to examine demographic and life-history changes in salmon stocks related to artificial propagation. Key metrics include the proportion of hatchery-origin fish spawning naturally (pHOS), effective population size and number of breeders, relative reproductive success (RRS), and a variety of indices of (meta) population structure within and among subbasins. Three general classes of genetic analyses were reported: genetic stock identification (GSI), parent-based tagging (PBT), and studies of environmental response via transcriptomics (RNA-sequencing) studies. These genetic approaches have great potential to estimate straying rates and functional connectivity among populations, and more generally, to investigate other uncertainties related to genetic, ecological, evolutionary, and functional changes in response to climate change and management actions.

There appears to be considerable, unrealized potential for synergy by combining data and analyses across projects to increase the scope and power of inference from GSI and PBT. Standardization of methods and data reporting would facilitate greater synthesis across these studies and help to focus more directly on how supplementation influences metapopulation structure and diversity. In particular, more synthesis and analysis could help to determine how observed differences in straying or relative reproductive success between natural and hatchery origin spawners, or among different sources of brood stock, affect the demographic parameters of metapopulations, and whether these relationships can be generalized to the whole basin and across species.

2006 Critical Uncertainty 29: What is the relationship between genetic diversity and ecological and evolutionary performance, and to what extent does the loss of stock diversity reduce the fitness, and hence survival rate and resilience, of remaining populations?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #29.

A. Progress and Criticality

Progress–Medium: Considerable theoretical knowledge exists about how loss of genetic diversity, both within and among populations, is likely to reduce long-term fitness and resilience. However, empirical data are limited, and the practical consequences are poorly understood. A number of genetic approaches have been developed and are now available to address this critical uncertainty in salmonids, but work on non-salmonid species has lagged.

Criticality–Priority: Long-term monitoring of the genetic diversity, fitness, and resilience of index populations remains a high priority. For most non-salmonid species, it will also be necessary to develop reliable genetic markers for long-term genetic monitoring, genetic stock identification (GSI), and parentage based tagging (PBT) as well as genome-enabled approaches (e.g., RNA sequencing, candidate genes) to link genetic variation and ecological performance. It will also be important to develop approaches to maintain or enhance genetic diversity.

B. Contributions from Fish and Wildlife Program projects

Long-term questions involving evolutionary performance and resilience of populations are very challenging to address. Two projects have begun to address this uncertainty in part for non-salmonid species. Project 2008-504-00, focused on white sturgeon, has identified a suite of DNA microsatellite loci to study population structure, gene flow and effective population size. Analyses of basic population genetic metrics such as heterozygosity, conformance to Hardy-Weinberg proportions, and allelic diversity have been completed. Much of the value of this project rests on its ability to track long-lived fish over many years in order to measure key population parameters. It also remains unclear whether the genetic differences detected among putative stocks of sturgeon indicate historical, biologically meaningful adaptations to specific areas, or are a recent consequence of isolation due to dams.

Project 2008-524-00, focused on Pacific lamprey, is currently developing and validating 96 single nucleotide polymorphisms (SNP) to identify breeding populations, track the parentage of juveniles, and ultimately identify the reproductive success of translocated adults and hatchery juveniles.

A noteworthy gap in Fish and Wildlife Program research to date is that none of the projects reviewed has explicitly addressed the relationship between genetic diversity and long-term fitness and resilience. On the other hand, many projects are generating information relevant to assessing the ecological and evolutionary performance of individual families and populations whose genetic diversity is being measured by other projects. Thus, there appears to be an opportunity to address this gap by initiating a study to synthesize and analyze relevant information that is already available from within the Columbia River Basin. Such an effort could provide useful recommendations for integrating future Program projects to ensure that long-term aspects of 2006 CU #29 will be addressed. This opportunity for greater synthesis is a more general case of the gap already identified for CU #28 (i.e., how supplementation influences metapopulation structure and diversity).

C. Additional Information

Much is known about the theoretical relationship between genetic diversity and the long-term fitness of populations (Reed and Frankham 2003), the implications for the resilience of metapopulations and ecosystems (Walker and Salt 2006), and food security for humans (Heal et al. 2004). Empirical support for these theoretical relationships based on long-term studies is still relatively limited, but compelling examples from outside the Columbia River Basin are described in recent textbooks on Conservation Genetics (e.g., Frankham et al. 2010, Allendorf et al. 2013).

2006 Critical Uncertainty 30: What are the differential effects of flow augmentation, transportation, and summer spill on "ocean type vs. reservoir type" fall Chinook?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #30.

A. Progress and Criticality

Progress–Medium: Considerable new knowledge has emerged from PIT tagging and otolith chemistry studies and statistical analyses by the Comparative Survival Study (CSS), but it appears that no study has explicitly investigated differences in the overall survival (i.e., return rate) of ocean type versus reservoir type fall Chinook smolts, although survival of hatchery subyearling versus yearling fall Chinook have been examined.

Criticality–Medium: Life history diversity promotes the resilience of populations and might be reduced by changes to hydrosystem operations that impact some life history types more than others. As it stands, this uncertainty is focused rather narrowly on just two life history types of fall Chinook.

B. Contributions from Fish and Wildlife Program projects

Three Program projects have contributed directly to addressing parts of this uncertainty. One project (Ann. Proj. Rept. 1993-029-00) used PIT tagging and detection arrays to assess the impact of hydrosystem operations on fish passage survival for all salmon species. Results to date indicate that spill is positively correlated with increased passage survival. However, more development of PIT-tag detectors in spillways is needed to improve estimates of survival because as spill has increased, the precision of estimates of survival and travel time through the hydrosystem has decreased. Also, more PIT-tag detection systems in upstream tributaries would help to identify sources of mortality.

A second project (Ann. Proj. Rept. 2003-032-00) has looked at the effects of flow, water temperature, gas supersaturation, and predation by smallmouth bass on fall Chinook. Otolith chemistry was used to determine the origin and rearing location of unmarked returning adults and identify areas that are productive in terms of abundance and diversity of life histories. No significant differences were found between subyearling and yearling life histories in terms of age and size at which they entered and exited the estuary, or rate of growth in the estuary. Most adult fall Chinook were estimated to have originated, reared, and overwintered in the lower Snake River, rather than its tributaries (Clearwater and Salmon rivers). Predation by nonnative smallmouth bass on juvenile Chinook in a section of the Lower Granite Dam pool near Lewiston was found to be higher than in the 1990s when Chinook abundance was much lower; unfortunately, percent mortality was not estimated for either life history type so the biological significance of this finding remains unknown.

Neither project has explicitly applied these relevant findings about passage survival, rearing in the estuary, or predation in the Lower Granite pool to address CU #30.

A third project, the Comparative Survival Study (CSS 2015 Annual Report; 1996-020-00) reported that the juvenile smolt transportation program does not mitigate for the adverse impacts of the operation of the FCRPS on subyearling fall Chinook groups that were analyzed. Twelve study cohorts showed significant benefit to adult returns from migrating in-river while five cohorts showed a significant transport benefit. Transport benefit appears to be related to in-river survival from Lower Granite Dam to Bonneville Dam, similar to that demonstrated for yearling Chinook and steelhead, with transport benefit decreasing as in-river survival increases. However, the CSS did not assess relative benefits for yearling fall Chinook salmon. Seasonal studies of PIT-tagged yearling smolts of wild and hatchery spring/summer Chinook indicate that smolt-to adult survival (SAR) tends to decrease from the beginning of the season (earliest fish to arrive at LGR) until the end (latest to arrive). This seasonal decline in SAR is typically steeper for bypassed fish that are returned to the river than for bypassed fish that are transported, which strongly suggests transportation benefits in most years for yearling Chinook smolts bypassed after May 1 (Smith et al. 2013).

Four other projects build capacity that could be used to address the uncertainty by contributing to the development of tools used for the sharing or analysis of relevant data. One project maintains the PTAGIS System used to manage all the PIT tag release and detection data. A second project is developing computer programs used to analyze tag capture-recapture data and to estimate sample size/statistical power of proposed studies. A third project is analyzing historical tagging data to understand the relationship between fish responses, environmental factors and anthropogenic effects. A fourth project is refining SNP-based genetic stock identification (GSI) and parent-based tagging (PBT) methods to complement data from PIT tagging studies.

Climate Change

Table 9. Climate change-theme[26] critical uncertainties in the 2006 Research Plan and the number of Fish and Wildlife Program projects that directly or potentially addressed each one.

ID	2006 Research Plan Critical Uncertainty (click to see table of specific projects)	Directly	Potential
31	Can integrated ecological monitoring be used to determine how climate change simultaneously affects fish and wildlife and the freshwater, estuarine, ocean, and terrestrial habitats and ecosystems that sustain them?	2	8
32	Can indices of climate change be used to better understand and predict interannual and interdecadal changes in production, abundance, diversity, and distribution of Columbia Basin fish and wildlife?	1	6
33	What long-term changes are predicted in the Columbia River Basin and the northeast Pacific Ocean, how will they affect the fish and wildlife in the region, and what actions can ameliorate increased water temperatures, decreased summer river flows, and other ecosystem changes?	2	11

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CUs #31, CU #32 and CU #33:

Even though these three critical uncertainties address very different, but important aspects of climate change in the Columbia River Basin, they are grouped together here because so few projects are actively examining the uncertainties.

A. Progress and Criticality

Progress–Medium: Moderate progress has been made toward understanding future climate change in the Columbia River Basin (including estuary, ocean and terrestrial habitats). However, little progress has been made in understanding how climate change will affect fish and wildlife and in developing strategic approaches to mitigate likely adverse effects.

Criticality–Priority: These issues will drive ongoing efforts to restore species and their habitats. That is, without an understanding of potential effects of climate change on the physical environment, management decisions about where and how to restore habitat may not succeed in the long term.

[26] For further background information on this theme, see the 2006 Research Plan summary, page 19, and the 2014 Fish and Wildlife Program strategy on Climate Change.

B. Contributions from Fish and Wildlife Program Projects

The Fish and Wildlife Program funds two projects that specifically address climate change in the Columbia River Basin. The first of these (Ann. Proj. Rept. 209-005-00) is developing genetic markers that can be used to identify thermal tolerance of salmonid stocks. Differential expression of genes across strains can indicate genetically determined differences in physiological responses and help to understand the potential for an adaptive response to thermal changes predicted to occur with climate change. In the second project (Ann. Proj. Rept. 2009-008-00), CRITFC is assisting member tribes (Nez Perce, Yakama, Warm Springs and Umatilla) to develop tools for investigating the potential impacts of and mitigation strategies for climate change to protect First Foods. Thus far, this has been accomplished by participating in and coordinating workshops (e.g., "International Columbia Basin Transboundary Climate and Hydrology Assessment Workshop") and collaborating with federal action agencies and other regional entities to review, develop, and enhance physical and biological climate models to identify impacts to tribal first foods. A number of other projects are collecting long-term monitoring data to determine status and trends of fish, wildlife or terrestrial vegetation. These projects are monitoring fish passage and water temperatures in tributaries; daily, seasonal annual and decadal changes in fish abundance and habitat quality in the estuary and ocean; or changes accompanying habitat restoration. In all instances, data from these projects would have to be evaluated and re-analyzed to determine their value in addressing climate change uncertainties.

While these projects address parts of the climate change critical uncertainties, the effort is too small to make significant progress toward addressing the uncertainties. A much larger collaborative effort uniting universities (mentioned below in "Additional Information") and others are necessary.

C. Additional Information

There is considerable climate change research being conducted primarily at universities and by federal agencies (e.g., University of Washington, Oregon State University, BPA, the Corps of Engineers, USBR, USGS and NOAA-Fisheries). The primary focus of much of the research is to develop, downscale, and fine-tune climate models to improve the confidence in climate predictions and to model the effects of those predictions on environmental resources, including fish and wildlife. Several studies have predicted aquatic refuges in the Columbia River Basin where fish populations might survive under predicted changes in hydrology and water temperature (Rieman et al. 2007, Wenger et al. 2011) including estimating changes in the interface between rain and snow and subsequent effects on snowmelt and runoff (Mantua et al. 2010, Wu et al. 2012, Dalton et al. 2013). Many models have downscaled air temperature to predict water temperature; however, it may be necessary to consider spatial and temporal differences between air and water (Arismendi et al. 2014). Because climate change has the potential to disrupt human activities, studies have also included stakeholder concerns (Jenni et al. 2014) and possible effects on tribal well-being (Montag et al. 2014). The US Forest Service's Rocky Mountain Research Station also hosts the NorWeST project, which provides high-resolution predictions of summer stream temperatures based on a comprehensive stream temperature database that was culled from more than 80 resource organizations. The NorWeST webpage includes stream temperature data and geospatial map outputs from a regional temperature model for Northwest USA. The NorWeST webpage also states “*a major goal of this project is to provide climate vulnerability and native trout refuge information to land managers and policymakers.*”

The Fish and Wildlife Program should play a more significant role integrating these efforts to benefit Columbia River Basin fish and wildlife.

Contaminants

Table 10. Contaminants-theme[27] critical uncertainties in the 2006 Research Plan and the number of Fish and Wildlife Program projects that directly or potentially addressed each one.

ID	2006 Research Plan Critical Uncertainty (click to see table of specific projects)	Directly	Indirectly
34	What is the distribution and concentration of toxics, including emerging contaminants, in the Columbia River Basin, and what are/have been their trends over time?	2	2
35	How do toxic substances, alone and in combination, affect fish and wildlife distribution and abundance, survival, and productivity?	1	5

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #34 and CU #35:

Even though these two critical uncertainties address very different but equally important aspects of contaminants in the Columbia River Basin (i.e., the distribution of compounds and the effects of those compounds on biota), they are grouped together here because so few Program projects are actively examining the uncertainties.

A. Progress and Criticality

Progress–Low: Very little progress has been made toward resolving these uncertainties in the Columbia River Basin, but more progress has been made elsewhere in the United States.

Criticality–Priority: Management actions such as habitat restoration or supplementation will not be successful if contaminants of ever-increasing variety and sources impair animal health. The potential for contaminants to negate restoration efforts is high, and thus the topic demands greater attention from the Fish and Wildlife Program.

B. Contributions from Fish and Wildlife Program Projects

There are three Program-funded projects that directly address uncertainties about the distribution and effects of contaminants in the Columbia River Basin. Pacific lamprey are the focal species in two projects (Ann. Proj. Repts. 2008-470-00 and 2008-524-00) and landlocked trout (Ann. Proj. Rept. 1995-013-00) is the focus of the third (i.e., no anadromous salmonids). There is concern about Pacific lamprey because they spend up to 10 years rearing in sediments that might contain mercury, pesticides, pharmaceuticals from wastewater, or legacy contaminants such as PCBs. The effect of these on the long-term survival of

[27] For additional background information on this theme, see the 2006 Research Plan summary, page 19 (Toxics), and the 2014 Fish and Wildlife Program strategy on water quality.

Pacific lamprey is not known. Concerns about landlocked trout are very site specific and come from high nutrient loading in their rearing ponds. All three projects are funded under the Tribal Accords, and there are many more questions about the distribution and effects of contaminants in the Columbia River than are currently being addressed. These projects are leading to management actions, as a goal of the Pacific lamprey projects is the establishment of Pacific lamprey aquaculture, which will require clean sediments. The trout pond project is exploring management options to reduce nutrient inputs. A number of other projects collect habitat and water quality data that could be used to explore the presence and effects of contaminants. The two projects mentioned above are concerned with Pacific lamprey culture, another is developing culture practices for white sturgeon (Ann. Proj. Rept. 1988-064-00), and yet another is exploring freshwater mussel restoration (Ann. Proj. Rept. 2002-037-00). The presence and effects of contaminants may negate the restoration goals of these projects.

C. Additional Information

The US Environmental Protection Agency (EPA) has declared that the Columbia River is a waterbody of great concern similar to the Florida Everglades, Chesapeake Bay, and the Great Lakes. Unlike those other waterbodies, however, no US EPA funds have been allocated to address water quality issues in the Columbia River. The US EPA does lead a Columbia River Toxic Reduction Working Group comprising representatives from federal, state, tribal, regional, university, and nongovernmental organizations. The workgroup has produced a number of white papers, including “Columbia River Basin: State of the River Report for Toxics” and “Strategy for Measuring, Documenting and Reducing Chemicals of Emerging Concern.” Other federal (USGS, NOAA-Fisheries, USFWS) and state (OR DEQ, WA DOE) agencies, and universities are also working independently to answer similar uncertainties. Significant chemical contaminants and detrimental effects have been found in a number of fish species in the Columbia River (Hinck et al. 2006) including salmon (Sloan et al. 2010), white sturgeon (Feist et al. 2005) and suckers (Christiansen et al. 2013). There remains a significant need to effectively incorporate this information into the Fish and Wildlife Program.

Non-Native Species

Table 11. Non-native species theme[28] critical uncertainties in the 2006 Research Plan and the number of Fish and Wildlife Program projects that directly or potentially addressed each one.

ID	2006 Research Plan Critical Uncertainty (click to see table of specific projects)	Directly	Potential
36	What is the current distribution and abundance of invasive and deliberately introduced nonnative species (e.g., the baseline condition), and how is this distribution related to existing habitat conditions (e.g., flow and temperature regimes, human development, restoration actions)?	1	9
37	To what extent do (or will) invasive and nonnative species significantly affect the potential recovery of native fish and wildlife species in the Columbia River Basin?	3	14
38	What are the primary pathways of introduction of invasive and nonnative species, and what methods could limit new introductions or mitigate the effects of currently established invasives?	0	2

Summary

Non-native species are arriving at an unprecedented pace in many parts of the Columbia River Basin. The potential for non-native species impacts is diverse by taxa and complex in ecological characteristics, but the suite of current studies addressing these problems is far narrower in scope. The novel ecosystems that are being created can only be understood with increasingly complex studies. The three questions posed in the 2006 Research Plan (Critical Uncertainties 36-38) acknowledge some of that complexity and provided a motivation and opportunity for proponents to develop broader, more complex, ecologically-based studies beyond the focused predator-prey studies of the 1980s and 1990s. This development has not occurred, however. Most studies have either continued to address non-natives bluntly through suppression efforts or only indirectly (with some monitoring) without hypothesis-driven objectives. This lack of focused effort is manifested as a nearly complete lack of studies identified as directly addressing the three critical uncertainties from the 2006 review.

The ISAB's non-native species report (ISAB 2008-4) provides context for understanding non-native species issues, and their Food Web Report (ISAB 2011-1) outlines limitations in our understanding of the scope of the non-native issue, including aspects such as species interactions and trophic relations. It is inadequately recognized that many of the non-native species have high potential to affect native fish recovery efforts. Many non-native species in the Basin include taxa other than fish, such as invasive Mollusca, aquatic vegetation, and still other taxa at lower trophic levels that may not yet have been identified as occurring in the Basin. In many cases, studies designed to deal with this reality are

[28] For additional background information on this theme, see the 2006 Research Plan summary, page 20 (Invasive Species), and the 2014 Fish and Wildlife Program strategy for non-native and invasive species.

completely unrepresented among existing projects. Non-native invertebrates may alter food webs for fishes and other vertebrates in ways not well understood or studied (ISAB 2011-1). In addition, studies that can predict and project how non-natives will fare relative to native species under climate changes are also lacking and will undoubtedly prove difficult to design and implement. Overall, the great challenge will be to design cost effective studies to test hypotheses to provide solid, implementable management recommendations on native and non-native interactions and how best to manage those interactions.

The widespread lack of specific scientific knowledge of the relationships between persistence and abundance of non-native fish species and habitat conditions throughout much of the Basin is compounded by the often ambivalent or conflicting values and attitudes by the public toward various non-native fish species. These values and attitudes are not necessarily science-based. In some cases, particular non-native fish species are favored and actively managed to enhance populations; in other cases, they are perceived as problems and, in some cases, suppression efforts are being pursued, on a case-by-case basis. There is inconsistency in how particular species are viewed and treated among water bodies, and in some cases, by different agencies and tribes within a water body (e.g., lake trout in Flathead Lake). In most cases, suppression is being used as an immediate remedy without thorough supporting information on the societal pressures leading to the suppression or of the ecological (i.e., science-based) roles of the non-native species in question. The Basin also has a history of often favoring coldwater species substitutions for coldwater species losses, when habitat changes and other trends in lower elevation areas suggest that coolwater species (e.g., perch, walleyes, smallmouth bass) and even some warmwater species (largemouth bass) may be more ecologically favored and thus more likely to provide fisheries in many cases (e.g., Projects 2001-028-00, 2008-109-00).

2006 Critical Uncertainty 36: What is the current distribution and abundance of invasive and deliberately introduced nonnative species (e.g., the baseline condition), and how is this distribution related to existing habitat conditions (e.g., flow and temperature regimes, human development, restoration actions)?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #36.

A. Progress and Criticality

Progress–Medium: Overall, the general lack of specific knowledge regarding the relation between persistence and abundance of non-native species and habitat conditions reflects both the lack of understanding of the complex interactions among organisms, as well as the often ambivalent or conflicting attitudes throughout much of the Basin about the roles of various non-native species.

Criticality–Medium: The uncertainty can be addressed through current distribution studies in relation to current habitat conditions. However, such snapshot studies of current conditions as indicated in the question do not necessarily forecast future conditions or show trends well. Understanding trends, probable future conditions, and the ecological basis for native species replacement by non-natives are even more vital concerns. A more future-oriented and ecologically based question would make it a much higher priority.

B. Contributions from Fish and Wildlife Program Projects

Only one project directly addresses this CU, i.e. the potential problems with juvenile fall Chinook salmon survival in Snake River reservoirs because of predation by non-native species (Ann. Proj. Rept. 2002-032-00). This study is strongly focused on the hydrosystem and on an important anadromous species potentially negatively affected by native and non-native predators in newly formed reservoir habitats. Reservoir habitats have the potential to serve as important rearing areas at some juvenile salmon life stages but may also function as habitat for piscivores, mostly non-native. Some life histories of fall Chinook thus have the potential to be reduced or eliminated by predation by non-natives such as smallmouth bass and walleye. It is worth considering if and, if so, how reservoir habitats could be made more conducive to providing good rearing conditions for juvenile salmonids, resulting in higher survival.

The remaining nine projects addressing this CU indirectly span a wide, often confusing, and potentially conflicting range of goals, objectives, and the tasks. At one extreme, the northern pikeminnow program (Ann. Proj. Rept. 1999-077-00) acts to reduce a *native* species, potentially aiding native salmonids but also potentially favoring non-native predators such as smallmouth bass, channel catfish, and walleye that can occupy similar habitats in the hydrosystem. Removal of northern pikeminnow faces much less potential resistance from angler groups, however, because northern pikeminnow are not a valued recreational species. Other projects are designed to favor non-native species whose potential negative effects on native species are being perceived as being outweighed by their potential as recreationally important species even though success of the programs has varied widely.

2006 Critical Uncertainty 37: To what extent do (or will) invasive and nonnative species significantly affect the potential recovery of native fish and wildlife species in the Columbia River Basin?

Overview of Ongoing Projects Addressing the Question and Additional Information

See [Table of FY 2015 projects addressing CU #37].

A. Progress and Criticality

Progress–Medium: Currently, more attention is being given to the effects of native species such as avian, pikeminnow, and pinniped predation than on the effects of non-native species. Some work is considering removal of non-native fish predators (e.g., Ann. Proj. Rept. 1991-019-01). The focus of many fish predator-prey studies in the past few decades has been on native pikeminnow; removal activities are still ongoing as a result of this research (Ann. Proj. Rept. 1990-077-00). In the meantime, non-natives such as smallmouth bass, walleye, northern pike, and lake trout have become more widely established as predators on salmonid juveniles, especially in reservoirs. Rearing and stocking of rainbow trout and brook trout into salmon and steelhead habitat continues to occur in some blocked areas. Efforts to re-establish salmonids into blocked areas will require a greater understanding of the fish communities present in those areas; non-native species are now often major components of those communities and habitats. Although non-native fishes may compete and prey upon native species, the non-natives at lower trophic levels may also increase to the point where food webs relied upon by native species are permanently altered.

Criticality–Priority: Existing and future non-natives have the potential to seriously impact Fish and Wildlife Program species recovery efforts. Benefits of habitat improvements to native species may be undermined if non-native species increase their occupancy of those habitats.

B. Contributions from Fish and Wildlife Program Projects

The three projects directly addressing this key question represent cases where project goals and objectives for restoration of desired species, both native and non-native, have not been met. Two of the studies involve a common problem, that of salmonids suffering low survival in reservoirs containing non-native predators. In none of the cases have clear paths toward success based on altering community composition been identified and thoroughly presented. In Rock Creek, efforts at restoring steelhead may be impeded by water shortage issues and exacerbated by non-native species (Ann. Proj. Rept. 2007-156-00).

The 14 studies indirectly addressing this critical uncertainty represent a wide range of situations from native species in lakes and reservoirs being affected by fish community changes to efforts in streams to isolate native fishes from potentially harmful non-natives. Efforts in small headwater streams may be less complex and physical isolation may be successful in protecting native species. Situations in reservoirs and larger lakes are more complicated (more species and more open to species introductions); success requires a greater understanding of the ecological relations among natives and non-natives. In Banks Lake, for example, efforts to restore kokanee fisheries have not met with success (Ann. Proj. Rept. 2001-028-00). Evidently this has occurred because of competition with lake whitefish, a non-native, and predation by bass and walleye. In blocked areas, more emphasis has been placed on repeated efforts to substitute a particular species, often a coldwater species, than on studies to determine why the substitution has not been successful.

C. Additional Information

When emigrating to the Columbia River estuary, salmonid smolts will encounter at least eight non-native predator and competitor fish species (Sanderson et al. 2009). In their review of the potential impacts of these fish and other non-natives on Basin salmonids, Sanderson et al. (2009) determined that juvenile salmonid losses due to predation by non-natives was (1) similar to that caused by passage through each of the eight dams on the Columbia and Snake rivers, (2) approximately equal to productivity declines due to habitat loss and degradation, and (3) comparable to harvest-related mortality rates experienced by adults. They concluded their review by documenting that few Program studies have investigated the impacts of nonindigenous species on native biota. Because of the potential impacts of these species, more resources should be channeled into this research area.

2006 Critical Uncertainty 38: What are the primary pathways of introduction of invasive and nonnative species, and what methods could limit new introductions or mitigate the effects of currently established invasives?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #38.

A. Progress and Criticality

Progress–Medium: Responses (if any) to introductions have been mostly reactionary rather than proactive and preventative, except for selected species such as zebra and quagga mussels that are well documented as highly harmful invasive species (IEAB 2010-1, IEAB 2013-2). In response to concerns for those species, state fish and wildlife agencies have implemented a coordinated watercraft inspection program on highways and at boat ramps to intercept quagga and zebra mussels, as well as other invasive species. In mitigating the effects of established invasive species, most emphasis has been placed on removal projects. For fish, liberalized fishing regulations, which are easier to implement and interpret than are food-web based projects that emphasize ecological relationships between and among species, are being used. In some cases, there is general disagreement between agencies as to what the appropriate response to non-natives species should be (e.g., lake trout in Flathead Lake). In Flathead Lake, popular recreational fisheries based on non-native fish (lake trout) clash with native fish restoration efforts (bull trout).

Criticality–Priority: Although natural resource agencies have become more cautious in their willingness to introduce non-native species, an increasingly mobile human population and increased global transportation capability has resulted in a greater likelihood of accidental or intentional introductions. How non-natives are most likely to enter ecosystems (primary pathways) and their likelihood of successfully becoming established are two areas in need of more investigation.

B. Contributions from Fish and Wildlife Program Projects

No projects fully addressed this question. Although the common ways in which non-native species can enter new waters are generally recognized (e.g., unintentional transport via boats, bait bucket releases and other water use activities, illegal stocking by “bucket biologists,” and even intentional stocking by agencies), their entry paths in particular instances are often not known. More research and monitoring are needed to detect pathways of entry.

The last part of the question, i.e., “mitigate the effects of currently established invasives,” is being addressed actively in two projects (Ann. Proj. Repts. 1991-019-01 and 2007-170-00). Weirs are used to maintain cutthroat trout and prevent hybridization of rainbow trout (Ann. Proj. Rept. 2007-170-00).

Efforts in Flathead Lake target lake trout removals to protect bull trout and westslope cutthroat trout. In both cases, liberalized regulations on the non-natives are used to increase removals; in one case the removals are being accelerated by targeted removals of lake trout. Well-designed monitoring activities are needed to assess benefits to native species to non-native species removals. It remains difficult to develop ecologically based food web and behavioral studies to identify underlying causes of observed variation in non-native species success in their new habitats.

C. Additional Information

In dealing with this critical uncertainty, an extensive literature exists from outside of the Columbia Basin on non-native introductions and pathways of movement. Such studies will be useful in identifying productive areas of investigation for addressing this critical uncertainty.

Human Development

Table 12. Human development theme[29] critical uncertainties in the 2006 Research Plan and the number of Fish and Wildlife Program projects that directly or potentially addressed each one.

ID	2006 Research Plan Critical Uncertainty (click to see table of specific projects)	Directly	Potential
39	What changes in human population density, distribution, and economic activity are expected over the next 20 years? 50 years?	0	3
40	How might the projected changes under different development scenarios affect land use patterns, protection and restoration efforts, habitats, and fish and wildlife populations?	0	12

2006 Critical Uncertainty 39: What changes in human population levels and their distribution, per capita income, and economic activity are expected over the next 20 years? 50 years?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #39.

A. Progress and Criticality

Progress–Mixed: Progress has been variable. It has been strong in some dimensions (e.g., population trends) and slow in others (e.g., evolving social preferences and institutions). Trends in population growth and shifts from rural to urban populations are expected to continue. The regional population is projected to double by 2100 from 13.5 million to 27 million (US Census Bureau, state agencies). These projected patterns provide a degree of confidence in terms of what to expect over the coming decades, although past trends do not always predict future trajectories. Our understanding of how changes in human population, land use, and economic transformation will affect fish and wildlife populations will be location-specific and depend on many factors, including the regulatory environment for land and water management and use in both agriculture and industry. As a result, progress has been greater in some locations than in others.

Criticality–Priority: This criticality places restoration actions within constraints imposed by human conditions and values. One broad trend that may continue is that as individuals' per capita incomes continue to rise, the value society places on fish, wildlife, ecosystem services and other natural "public goods" may rise relative to the value they place on commodities or the weight they assign to costs such as the cost of energy. In the past, this pattern has shifted society's "willingness to pay" in favor of doing more to protect the environment, and this shift can be expected to continue. However, other influences, such as domestic and international market forces or technological changes, have the potential to offset

[29] For additional background information on this theme, see the 2006 Research Plan summary, page 21.

or reinforce recent patterns, and these influences are highly uncertain. Moreover, unlike other uncertainties related to knowable biological relationships, the nature of "future influences of human change" will always be a moving target, making it impossible to fully resolve or eliminate this uncertainty.

B. Contributions from Fish and Wildlife Program Projects

No projects directly addressed this uncertainty. The Climate Change Impacts and CHaMP projects are relevant to this theme, but have not reduced this uncertainty.

C. Additional Information

Federal and regional demographic projections can provide a basis for population and income growth by county (e.g., Portland State University Population Research Center). More detailed projections are made at county and city levels. Some research projects have made more detailed projections of land use change (e.g., Willamette River Basin Atlas 2002, Baker et al. 2004, Willamette Water 2100, Byrd et al. 2010). How the general patterns will affect habitats, water quality, and air quality will depend on site-specific changes and federal, state, and local regulations, as well as public attitudes. Some rural areas will continue to see declining populations, others may rise where recreation and "amenity economies" grow. Rural areas surrounding existing population centers are more likely to experience substantial conversion of land cover and land use.

2006 Critical Uncertainty 40: How might the projected changes under different development scenarios affect land use patterns, environmental quality, protection and restoration efforts, habitats, and fish and wildlife populations?

Overview of Ongoing Projects Addressing the Question and Additional Information

See [Table of FY 2015 projects addressing CU #40].

A. Progress and Criticality

Progress–Low: Human populations and land cover in the Columbia River Basin are certain to change over the next century. However, it is difficult to predict the complex social, institutional, and political processes that will accompany population and economic growth, or how these changes will continue to affect fish and wildlife. Almost all Program projects have focused on status and past trends in habitats and fish and wildlife populations, and few if any explicitly quantify the potential responses of fish and wildlife to future changes in human activity.

Criticality–Priority: Responses in markets, in legislation, and in actions by other institutions governing collective actions related to public interests are highly uncertain – and critical to the success of the Fish and Wildlife Program. The Program identifies and responds to past changes, but future changes and impacts are ignored in most cases. Models that include socioeconomic components and their influences on the landscape and on fish and wildlife habitats and populations can provide a basis for projecting social as well as ecological outcomes. Though such approaches have their own sources of uncertainty, empirically based models can provide a range of likely trajectories that can be used to identify beneficial public policy options and potential management actions.

B. Contributions from Fish and Wildlife Program Projects

No projects address this uncertainty. The Climate Change Impacts and CHaMP projects may be relevant, but that will ultimately depend on the results produced.

One project with a potential connection with this question is examining freshwater mussels in the Middle and North Fork John Day and Umatilla rivers. The project is designed to understand reasons for the decline in mussel abundance and to improve the success of restoration actions. It is suggested that agricultural chemical use may be one of the causes of mussel decline. To the extent that this connection with agricultural chemicals is confirmed, there is a potential connection with land use patterns, protection, and restoration efforts, but this project is not addressing projected changes under different development scenarios.

A number of other projects were identified that focus on mitigation, including fish passage, land purchases, restoration, and monitoring. These potentially address the uncertainty to the extent that these projects provide evidence of the potential success of mitigation for human activities such as land use change and hydrosystem infrastructure and operations. Though the information obtained in the projects could be used to assess future development scenarios, none addresses projected changes under different development scenarios. The impact of future land use changes under different development scenarios on fish and wildlife may be mitigated if these kinds of mitigation actions are (a) found to be successful and transferable and (b) are incorporated into or combined with future land use changes.

C. Additional Information

The impacts of human system changes on the use of land and other resources, and the consequential effects on fish and wildlife, are the subjects of a substantial literature (see for example, Bateman et al. 2013, Rabotyagov et al. 2014), including studies for the Pacific Northwest (Azuma et al. 2014, Radeloff et al. 2012). As noted in the previous topic, several research projects in the Columbia River Basin have developed detailed projections of land use change and modeled the consequences for fish and wildlife populations (e.g., Willamette River Basin Atlas 2002, Baker et al. 2004, Willamette Water 2100). In addition, several major projects throughout the United States predict resource responses to future change (e.g., Lawler et al. 2014, Radeloff 2013, Steinitz et al. 2003, Grimm and Redman 2004). Detailed empirically based models of coupled human-natural systems can provide a better understanding of the linkages and feedbacks between human and biophysical system components and thus enable an evaluation of policies and management and restoration actions within the Columbia Basin (see Levin et al. 2013).

Monitoring and Evaluation

Table 13. Monitoring and evaluation theme[30] critical uncertainties in the 2006 Research Plan and the number of Fish and Wildlife Program projects that directly or potentially addressed each one.

ID	2006 Research Plan Critical Uncertainty (click to see table of specific projects)	Directly	Potential
41	Can a common probabilistic (statistical) site selection procedure for population and habitat status and trend monitoring be developed cooperatively?	3	4
42	Can a scientifically credible trend monitoring procedure based on remote sensing, photography, and data layers in a GIS format be developed?	2	10
43	Can empirical (e.g., regression) models for prediction of current abundance or presence-absence of focal species concurrent with the collection of data on status and trends of wildlife and fish populations and habitat be developed?	6	14
44	Make best professional judgment, based on available data, as to whether any new research in the spirit of the Intensive Watershed Monitoring approach should be instigated immediately. Most new intensive research should arise as a result of the interaction of existing inventory data with new data arising in population and habitat status and trend monitoring.	1	4

Summary

There have been substantial improvements in the ability of projects to collect monitoring and evaluation data and to improve data quality. This has been due to standardized protocols (e.g., CHaMP), technological progress (e.g., new and better tagging methods including genetic stock identification and parentage based tagging; GIS and remote sensing tools are now ubiquitous), and a stronger focus on monitoring during project reviews at various levels. Similarly, analytical methodology is much improved in the last 10 years.

It is well accepted that sound statistical planning for monitoring is critical to ensure proper evaluation of project effectiveness takes place. Fish and Wildlife Program projects should continue to apply robust statistical design in their monitoring and evaluation of projects so that projects can estimate effects due to management actions with appropriate resolution and have sufficient power to detect biologically meaningful results in a timely fashion. Monitoring and evaluation data also provide information for estimating parameters in models of climate change.

[30] See the 2006 Research Plan, page 21, for background information on this theme.

Some standardized protocols have been developed (e.g., CHaMP, also see www.monitoringmethods.org for other examples), but there are still areas where improvements are needed. For example:

- There is a need to establish a regionally accepted framework for operational loss assessments, (see Ann. Proj. Rept. 2002-011-00 - Kootenai River Operational Loss Assessment).
- Fish in/fish out methodologies are critical for evaluating habitat restoration activities, but these methods are site specific, and it is unclear if knowledge transfer is occurring in the Basin.
- Methodologies for evaluating the cumulative impacts of many small projects are particularly underdeveloped.
- Methodologies for effectively monitoring lamprey and other species are underdeveloped.
- Data gaps exist, and it is not clear of the value of this information and who should be responsible for collecting it (e.g., fish mass metrics for adults return).

A higher-level review with stakeholders would be useful in identifying additional concerns with monitoring and evaluation methodology.

2006 Critical Uncertainty 41: Can a common probabilistic (statistical) site selection procedure for population and habitat status and trend monitoring be developed cooperatively?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #41.

A. Progress and Criticality

Progress—Medium: Standardized, basinwide protocols have been established for monitoring habitat and populations (e.g., CHaMP, ISEMP, AEM, www.monitoringmethods.org). Adopting common monitoring methods has advantages because results become comparable across projects and knowledge is more readily transmitted. Standardized protocols have now been deployed at the individual project level. There appears, however, to be a lack of a basinwide probabilistic approach to selecting monitoring habitat and populations that would allow the results from project-specific studies to be aggregated into a (albeit simple) summary at the basin level. A common approach also lends itself to data mining of studies because their evaluations are comparable.

The key tradeoff is between selecting individual designs that works best for each projects' objectives versus selecting a common design that may be less than optimal for some projects but allows results to be easily compared and aggregated for basinwide inference.

Criticality–High: While common procedures allow results to be compared from different projects and allow results from different projects to be aggregated across larger spatial scales, there is always a tradeoff. Some projects should be monitored using a universal sampling program, while others should be monitored using site-specific programs. When projects are assessed during planning stages, this tradeoff should be evaluated.

B. Contributions from Fish and Wildlife Program Project

Standardized, basinwide protocols have been established for monitoring habitat and populations (e.g., CHaMP, ISEMP, AEM, www.monitoringmethods.org). These protocols have been effectively deployed at the project level (e.g., before/after impact/control designs to evaluate effectiveness of a specific habitat improvement) where the choice of a reference site can be quite difficult and probabilistic methods are seldom used.

CHaMP was originally designed for evaluating summer habitat, but somewhat different protocols are needed for measuring winter habitat status and trends. Monitoring winter habitat may become more important as climate change effects become more pronounced.

Population monitoring as smolts move out and adults return to the Basin is well established (e.g., CSS) with a coordinated use of common tools and sampling dictated by the locations of the dams. Population monitoring as adults return to terminal areas is project specific with protocols adapted to site-specific factors.

Project 2006-006-00 (Habitat Evaluation project) uses simple accounting procedures to enumerate habitat gains and losses and is not based on statistical sampling.

Project 2003-007-00 (Lower Columbia River Estuary Ecosystem Monitoring) used a probabilistic site selection procedure to select sites for long term monitoring. In the first project, they standardized sampling at a fixed set of "trend" sites and no longer select new sites. This will increase the power to detect trends ("index sites"), but now it is difficult to compute an estuary wide measure.

Project 2008-007-00 (Upper Columbia United Tribes Monitoring and Evaluation Program) used a stratified-random sampling design to select a total of 25 reference sites and another 71 sites have been selected for monitoring of ecological change. They used standardized monitoring methods for vegetation and vertebrate sampling. This is a common statistical design, but it would be difficult to roll up with other basinwide studies because of a lack of a common monitoring design.

It is reassuring that good statistical methods are being implemented throughout the Basin, but these projects also demonstrate the wide number of different probabilistic sampling schemes being used that are tailored to the needs of the individual projects. A higher level review (e.g., by the ISAB/ISRP) may encourage use of methods that provide information that is more easily aggregated across projects. For example, the use of CHaMP makes it easier to conduct higher level assessments.

C. Additional Information

Maas-Hebner et al. (2015) review problems encountered when trying to integrate data from separate monitoring designs for status and trend monitoring. They also provide examples of spatially extensive status and trend monitoring programs for aquatic ecosystems.

There are two successful national monitoring programs that are used in the Basin. The US EPA Environmental Monitoring and Assessment Program (EMAP) operated from 1990 to 2006 and used a large scale probabilistic sampling design to assess aquatic ecosystem condition. Herger et al. (2007) used this information to evaluate the ecological condition of wadeable streams of the interior Columbia River Basin**.** The National Aquatic Resource Survey (Olsen et al. 2015) is a continuation of EMAP and uses a generalized random tessellation stratified design (GRTS) that provides nationally consistent and scientifically defensible assessments of the waters of the United States at different spatial scales. This design can be used to track changes over time and can also be used to predict stream condition at non-monitored locations. Gitzen et al. (2012) discuss this type of design and other designs to provide useful and meaningful information from long-term ecological programs.

2006 Critical Uncertainty 42: Can a scientifically credible trend monitoring procedure based on remote sensing, photography, and data layers in a GIS format be developed?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #42.

A. Progress and Criticality

Progress–High: There has been a great deal of technological progress in remote sensing, GIS methods, photography and other methods of collecting data. These methods are being used for directly observable attributes such as channel morphology; land usage; and higher level vegetation changes, etc. In some cases, data can be collected from the air (e.g., counting redds in clear streams). However, it is unlikely that fish will be directly observable using remote sensing methods. Aquatic vegetation is still difficult to monitor. The key limitation in adopting these methods is a lack of resources in individual projects to investigate and implement newer methods.

Criticality–Medium: Projects are naturally moving towards these newer technologies as their costs of usage decline and as personnel become more familiar with their use. Adoption could be quicker if basinwide mandates for use of certain technologies were implemented.

B. Contributions from Fish and Wildlife Program Projects

Both the ISEMP and CHaMP projects collect data at various resolutions, with some of the data collected by photography and remote sensing. Neither project relies exclusively on remote sensing information as part of the monitoring plan. Many of the other projects use remote sensing data and photography to monitor habitats. GIS systems are extensively used throughout the system to hold and display data.

C. Additional Information

The remote sensing discipline is evolving rapidly. For example, Lawley et al. (2016) provide a review of the integrated use of site based and remote sensing methods for monitoring vegetation in Australia. They identified those indicators of vegetation quality that are best measured using traditional site-based methods and those that are more readily detectable using remote sensing methods. They recommend further work to effectively integrate the two approaches. Finkl and Makowski (2014) review methods for remote sensing and modeling as they apply to the coastal marine environment. Pettorelli et al. (2014) introduce a review that shows how integrating remote sensing into ecological research promotes a better understanding of the mechanisms shaping current changes in biodiversity patterns and improves conservation efforts.

2006 Critical Uncertainty 43: Can empirical (e.g., regression) models for prediction of current abundance or presence-absence of focal species concurrent with the collection of data on status and trends of wildlife and fish populations and habitat be developed?

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #43.

A. Progress and Criticality

Progress–High: Regression models can work well for short-term predictions, but current time series are often too short to deal with effects that occur on decadal levels. Moreover, these models may be inadequate to study the effects of climate change at the boundary or outside the range of the current data series. Regression models are difficult to develop if an understanding of the causal mechanisms underlying the relationships are unknown because it is unclear which variables should be used as predictors.

Criticality–High: Empirical models are critically important because they often indicate variables that are most highly associated with a response and measure the effect of variables most amenable to management actions. While these are solely statistical relationships, such relationship often provide information about the potential impact of management actions that affect important variables.

B. Contributions from Fish and Wildlife Program Projects

Many of the direct projects focused on regression models to predict population parameters based both on data collected as part of status and trend monitoring and other data now routinely available (e.g., ocean conditions). ISEMP provides many examples of regression methods to fit fish-habitat relationships (the NREI model, quantile random forest model, patch occupancy model) to predict fish densities given habitat information. Projects 2003-009-00 (Canada-USA Shelf Salmon Survival Study) and Project 1998-014-00 (Ocean Survival of Salmonids) developed regression relationships between ocean survival of juveniles and time of entry and/or ocean conditions.

C. Additional Information

Regression methods are standard statistical methods routinely used in virtually any monitoring program. Boyce et al. (2016) reviewed how models of habitat selection can be used to estimate abundance at large scales. Maas-Hebner et al. (2015) review problems encountered when using statistical methods for status and trend monitoring especially when data collected at different spatial scales. Occupancy modeling (Mackenzie 2005) is a well-established statistical method to predict presence/absence given other covariates. Recently, Cao et al. (2016) did an extensive review of over 70 peer reviewed publication on species modeling as function of landscape-level environmental covariates. They further developed models to estimate fish abundance in wadeable streams in Illinois using random forest regression methods.

2006 Critical Uncertainty 44: Make best professional judgment, based on available data, as to whether any new research in the spirit of the Intensive Watershed Monitoring approach should be instigated immediately. Most new intensive research should arise as a result of the interaction of existing inventory data with new data arising in population and habitat status and trend monitoring.

Overview of Ongoing Projects Addressing the Question and Additional Information

See Table of FY 2015 projects addressing CU #44.

A. Progress and Criticality

Although listed in the 2006 Research Plan as a critical uncertainty, this is more of a statement on implementing research, monitoring, and evaluation. In addition, the statement was difficult to understand, so we interpreted it as: "What new intensive research might achieve synergies from combining existing inventory data with new data arising from population and habitat status and trend monitoring?"

Progress–Low: It has not been clear who should take a higher-level view of where information gaps arise, thus requiring new research. The ISAB occasionally takes this role. For example, ISAB 2015-1 reviewed evidence for density dependence and found that it appears to be operating in the Basin even though population levels are thought to be below historical levels. A targeted intensive research program may be needed to determine why this is happening. Additionally, supplementation has implications that require extensive and coordinated monitoring to resolve (ISRP/ISAB 2005-15).

Criticality–Medium: Criticality is judged to be moderate as many universities, NGOs, and federal, tribal, and state agencies have a keen interest in the Columbia Basin and are continually looking for new research opportunities. The ISAB may play an important role in reviewing and looking for communalities among these research programs.

B. Contributions from Fish and Wildlife Program Projects

Since 2006, ISEMP has conducted intensively monitored watershed (IMW) research and CHaMP was initiated. The ISEMP and CHaMP projects have now been used for many years, and many of the protocols and analysis methods have been adopted throughout the system. These programs, however, have not generated (nor are they expected to generate) any emerging issues needing further intensive research.

C. Additional Information

Monitoring and evaluation is reviewed at many levels in many basins. For example, the Washington State Salmon Recovery Funding Board holds annual meetings to examine what type of monitoring is needed for the future to complement work done by BPA. The Missouri River Recovery Program is looking at recovery efforts for endangered terns and sturgeons. While the issues are different, there are similarities to problems with the Columbia Basin on habitat loss, impact of dams, and water quality issues. The Great Lakes Water Quality Agreement of 2012 established bi-national priorities for science and action to address current and future threats to the quality of the Water of the Great Lakes that focuses on many of the emerging problems of contaminants, invasive species, and habitat.

Appendix A. Challenges for Prioritizing Uncertainties to Guide Management Decisions

In the Council's February 23, 2015 review request to the ISAB and ISRP, the Council asked for:

> ***"Scientific input on identifying priorities among the critical uncertainties.*** Although all the uncertainties identified should be critical***, those for which information will have greatest benefit*** on population status, ***both in terms of viability assessments and in terms of meeting mitigation obligations***, should be identified. This information is particularly important to the Council because it can help frame strategies for improving fish and wildlife restoration and management in a cost-effective manner. Sequencing research to address some uncertainties first may also be logical if the results inform approaches or provide analysis needed to address other uncertainties. In this effort, the Council encourages the science panels to use the Program's scientific-related prioritization criteria and, as applicable, the Risk-Uncertainty Matrix (pages 102-104)." (bold, italics added)

Our Critical Uncertainty (CU) Review has followed a process that makes a range of assumptions and has some obvious limitations. Some of the challenges encountered are summarized here in order for (a) the current review to be interpreted with these factors in mind and (b) these challenges to be highlighted and be addressed in the future.

A key challenge for judging which uncertainties are critical and which will have the greatest benefit if they are resolved is that these judgments involve consideration of their socioeconomic, legal and political context, and not only the factors that contribute to biophysical uncertainty. Furthermore, judgments about the relative value of one piece of information over another depend on an understanding of how the information might be used to further the Council's objectives. For example, will it enable success in meeting mitigation obligations or improve the odds of finding a more cost-effective way to rebuild fish populations?

The stated research principles for the Program require that priorities be set based on their relevance to management decisions, and management decisions are recognized to depend on: (a) cost, (b) time required, (c) legal relevance, (d) underlying assumptions of the Program, and (e) expected effectiveness of outcomes. The first criterion, the cost of a particular management action (or in the case of acquiring information, the cost of the research), is usually unknown and omitted from consideration in setting priorities among uncertainties. The omission of cost information hinders our ability to target uncertainties cost-effectively.

The criterion of "expected effectiveness of outcomes" refers to the outcome of a decision to act (implementation of a measure) that has potential benefit to rebuild naturally spawning fish populations. However, in order to incorporate this criterion into a judgment about whether an uncertainty is critical would require knowing what acts or measures are being considered and how the information, if collected, would contribute to making better decisions. Indeed, the full range of possible management actions is hard to ascertain given the many complex legal and political constraints that limit or dictate the range of specific management acts, and this makes it even more difficult to connect a critical uncertainty to the expected effectiveness of a specific outcome.

These complex relationships between making decisions and acquiring information are recognized in the literature on organizations (e.g., Arrow 1974; Tirole 1986), which can be applied to organizations with scientific goals such as the Fish and Wildlife Program. In this literature, uncertainty is defined as "the difference between the amount of information required to perform the task and the amount of information already possessed by the organization" (Galbraith 1973). To judge if a specific information gap is critical requires (a) knowing what actions or tasks are being considered by the organization, (b) the value to the organization of completing each task or action, and (c) how eliminating the specific information gap would improve the outcome compared to what would have been possible without the information.

Prioritizing research and actions to fulfill the objectives of the Program is complex and multi-dimensional. Like any organization, decisions are made based on information, and when information is costly, considerable resources are devoted to deciding whether to collect more information, what kind of information to collect, and how to go about it. These are among the most important decisions that organizations make.

The challenges for decision makers are parallel to the challenges described above for prioritizing critical uncertainties. Decision makers need to enumerate the set of possible management actions and then determine which actions to take, which will always depend on the kinds and quality of information at their disposal, the information potentially at their disposal (if they choose to gather more information), and knowing the feasibility, cost, and lag-time for gathering more information if it is needed prior to making a particular decision.

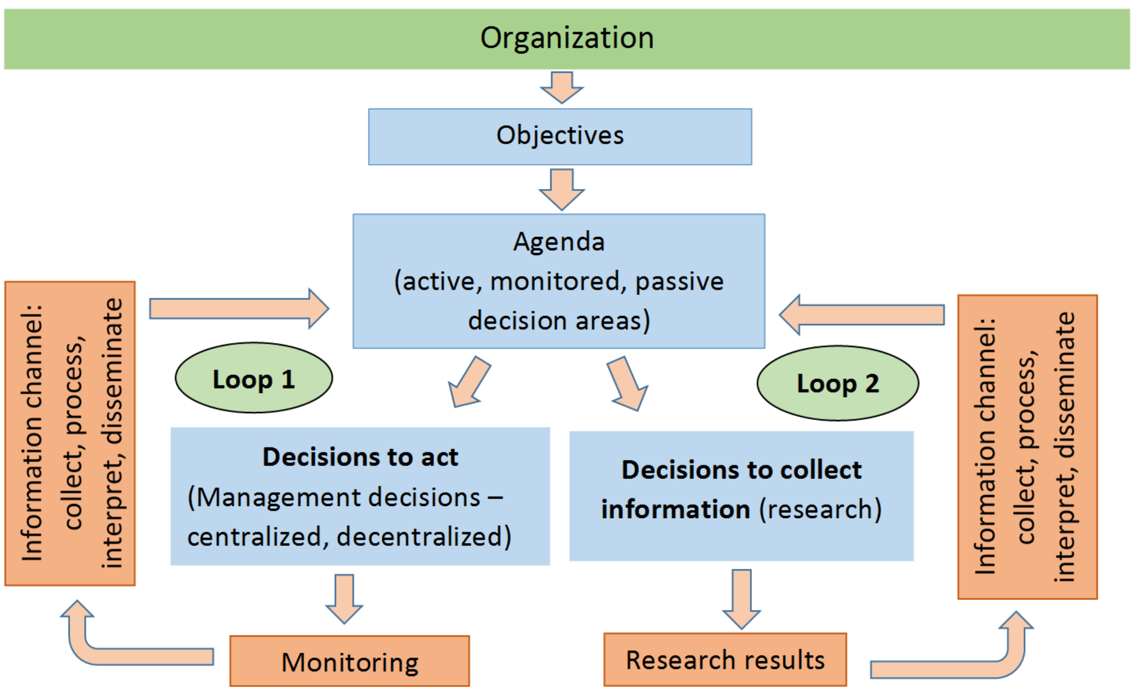
The situation represents a dilemma for both decision makers to take action, as well as for scientists being asked to identify and prioritize critical uncertainties. Decision makers want to know from scientists what additional information is "critical," but what is critical depends on the decisions they (the decision makers) are considering making. On the other hand, scientists are asked to prioritize uncertainties, but this depends on which information would be most useful to the Council or other decision makers, i.e., what would help them make better decisions. Given this "chicken-or-egg" dilemma, closer coordination seems desirable between what decision makers need to know in order to act and what scientists see as researchable questions to answer.

Organizations, information, and decision making

The relationship between research that addresses critical uncertainties and the management decisions that have the attention of the Council illustrates the challenges identified in established scholarship on the economics of information and how organizations function. This standard framework provides a common way to think about the relationship between management decisions and scientific research and complements the Program's adaptive management framework. A brief summary is presented here.

The key elements of an organization, as depicted in Figure A.1 below, are (a) objectives, (b) setting agendas, (c) taking actions to further the organization's objectives (Loop 1) or making decisions to collect more information (Loop 2) before taking actions. The organization makes progress toward its objectives by taking actions in the lower left of the diagram, in the cycle labeled Loop 1. Often, however, if insufficient information is available to make the best "Decision to act," a "Decision to collect information" is instead made (Loop 2), so that with this additional information, a Loop 1 decision can be made in the future. Adaptive management could be characterized as taking actions that are intended to serve both Loop 1 and Loop 2 purposes simultaneously.

Figure A.1. Conceptual relationships in an organization



This framework is consistent with, and similar to, the 2014 Program's Framework and adaptive management approach, characterized below in Figure A.2 from the Program (page 31). This is the Program's adaptive management flowchart, which includes similar elements.[31] Figure A.1 draws attention to some aspects of an organization's decision making that are less explicit in Figure A.2.

[31] The ISAB and ISRP have written extensively on the adaptive management approach and challenges in implementing the approach in the Fish and Wildlife Program. Specifically, see the ISRP's Retrospective Report 2007: Adaptive Management in Columbia River Basin (ISRP 2008-4) and the ISAB's Review of the 2009 Fish and Wildlife Program (ISAB 2013-1; page 2 and throughout).

More generally, the framework represented in Figure A.1 reflects an understanding that an "organization" is an entity created to achieve the benefits of collective action. The purpose of an organization is typically to exploit the fact that many decisions require participation of many individuals for their effectiveness. One particular issue that is absolutely central to the understanding of organizations is uncertainty. How organizations make decisions in the face of uncertainty, given that information is costly, is fundamental to understanding what organizations are all about.

Critical to how organizations work is the "information channels" that are created to organize the flow, interpretation, and processing of information. The value and desirability of creating organizations is partially determined by the characteristics of these information flows. There are benefits and costs associated with information channels, and organizations are to a great extent "processors" of information. The optimal choice of internal communication structures within an organization is "a vastly difficult question" (Arrow 1974).

Figure A.2. Components of Fish and Wildlife Program Framework

From page 31 in the 2014 Fish and Wildlife Program: Linkages between program vision, goals, objectives, and indicators track how successful program strategies are progressing toward the goals and objectives.

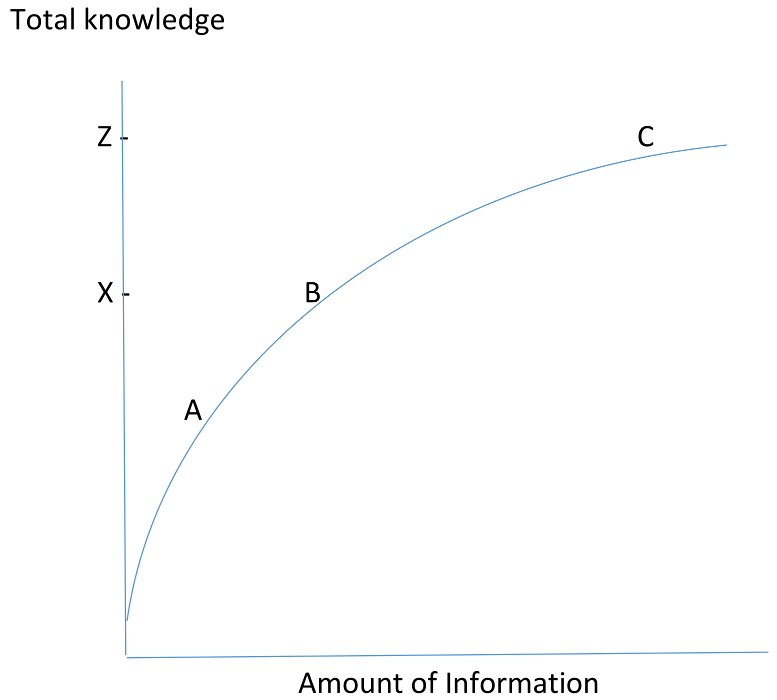
To understand information channels and flows, it is important to understand not only that information is costly but that the collection of information (e.g., research) is an irreversible capital investment (in "knowledge"). From a particular starting point or reference point, the costs of additional information can vary in different directions (often evolving by chance, in path-dependent directions from a given starting point).

The management decisions or “agenda” of an organization are the possible actions or measures under consideration. This set should include all the possible actions on the radar, or even off the radar, of the organization. These include actions that directly further the objectives of the organization (Loop 1), and actions to collect more information (Loop 2) with the idea that this information, once collected, will make it possible to act in ways that further the organization’s objectives (Loop 1). Decision areas within an organization can be active, monitored, or passive. Most organizations can identify these decision processes (Loops 1 and 2) and recognize how the objective of Loop 2 is to improve decision making in Loop 1 for management decisions or, in the language of the Program, “measures.” In the case of the Program, Loop 2 is research to collect more information (eliminate uncertainties) that will enable better “Loop 1” decisions to be made (measures that directly benefit fish).

What Figure A.1 highlights is the way that management decisions are inseparable from decisions to collect information (in the service of making better management decisions). Identifying which knowledge gaps are high priority or “critical” without linking them to specific potential actions under consideration by management may be possible in some cases where the need for information is obvious, but in many cases there may be too little information to assign a priority to knowledge gaps credibly. Moreover, a decision about which kind of information to collect should depend on both the cost of collecting the information and the value (for making a specific management decision) of the information once collected.

As more is known about a given relationship, the marginal value of additional information diminishes. This “diminishing marginal value” relationship (Figure A.3) is a core concept in economics, one that can be applied to the economics of information. For example, at point A little is known and an investment in research will improve our knowledge greatly; an investment will improve knowledge somewhat less at point B; and more investment in information will have little added effect at point C. But this recognition by itself is not sufficient, because the value of the information collected will depend on how it can be used. For example, there may be special circumstances where a threshold amount of information (e.g., at point Z) is necessary for making a reliable management decision. If so, gaining that threshold amount on information may be cost-effective even if the marginal returns (to research) near Z are small?

Figure A.3. Diminishing value of investing in information.



One way to represent the additional criteria that are part of management decisions would be to modify the "risk-uncertainty" matrix that has been used in the Program to frame priorities for monitoring efforts (FWP, p. 102), so that it includes both the cost of information, and the direct and indirect ways that information is valuable toward fulfilling the objectives of the Program (see Table A.1 below). Here we propose a revision of the risk-uncertainty matrix to retain the spirit of its underlying tradeoffs, while reflecting more dimensions related to decision making.

Table A.1 represents three dimensions of prioritizing. First, there is a need to link specific kinds of information to specific management decisions and to recognize how those management decisions might succeed in rebuilding naturally spawning fish populations. Those linkages would facilitate distinguishing between the potential benefits of actions that would have large benefits toward Program objectives (e.g., ones that would have long-lasting, basinwide benefits versus ones that would be limited to a subbasin for a short period of time).

Second, if we interpret "scientific uncertainty" in the Program matrix to be a gap in knowledge that, if filled, will have value, then we can refer to this as "the value of new information." In cases where substantial information on a particular theme has already been amassed, the value of new information might be lower than for other themes (e.g. sturgeon) where little is currently known.

Finally, costs are essential to take into account. Given a limited budget, the progress that can be made toward Program objectives will be proportional to the cost-effectiveness of the choices made regarding how best to achieve those objectives. The cost of information useful to the Program can often vary by a factor of 10, as demonstrated in the IEAB report "Cost-effectiveness of Fish Tagging Technologies and Programs in the Basin" (IEAB 2013-1). For example, if there are two alternative approaches to address a given research question, and approach A costs 10 times as much as approach B, then with a limited research budget, it could take 50 years to achieve the objective with A rather than 5 years with approach B.

A three-dimensional decision matrix

Given a limited budget to fund research, the total value of the information generated in pursuit of Program objectives will be maximized when we get the greatest benefit from management decisions (both decisions to act and decisions to acquire more information) in terms of value per dollar of funding. For example, more costly basinwide research may be justified to the extent that the spatial scale of potential benefits is also basinwide.

To summarize, three key elements of Program decisions are recognized in Table 1 as (a) costs, (b) the expected value of new information, and (c) the potential benefits from direct actions—ones that may be made possible with that new information. The numbers in the table are hypothetical, suggesting how the relative estimates of potential benefits to the Program, the value of new information, and the cost of that new information might range from 1 to 5.

Table A.1. Conceptual matrix for priority ranking of actions based on potential benefit, information needs, and costs

		Potential benefit from a direct action to further FWP objectives (a measure or 'terminal act')			
		Low		High	
		Expected value of new information (reducing level of uncertainty) relevant to proposed action:			
		Low	High	Low	High
Expected cost of information:	High	1	2	3	4
	Low	2	3	4	5

Explanatory notes

a. Priority order (1=low to 5=high) is suggestive only of relative rankings

b. "Value of direct action" refers to direct measures or "terminal acts" to rebuild naturally reproducing fish populations.

c. Value of information (reflecting level of uncertainty)

d. Cost refers to the cost of collecting needed information

Implications

We conclude that it is a daunting challenge to quantify and rank the values, benefits, and costs associated with an expansive and evolving set of potential management decisions and a comprehensive set of knowledge gaps that, if eliminated, could be beneficial to the Program.

This challenge of simultaneously needing to know what management decisions are feasible, and what information is most valuable to those decisions, is recognized in the Program. Figure A.2 is suggestive of a two-way flow of information and decisions along these lines. Additional efforts to address this in more coordinated and explicit ways would help provide specific and reliable guidance. The Program has identified strategies and related measures (FWP, p. 38-100). A more extensive list of measures, including "potential measures" that would be considered if better information were available, would make it possible to evaluate specific uncertainties relevant to specific measures. Examples can be identified where strategies have been linked to measures. However, more specific and full consideration of the criteria relevant to prioritizing uncertainties would be beneficial.

To illustrate what might be involved in a more detailed and explicit approach, a set of likely steps is proposed here following the framework in Figure A.1:

First, one would need to identify an agenda decision area, and then a specific management decision that is under consideration. Second, one would want to make some judgment about the expected magnitude of benefits for a specific management action, considering things like:

- Importance of benefits (e.g., legal imperative, avoidance of extinction)
- Certainty of the benefits (probability of success)
- Spatial scale of benefits
- Duration of benefits
- Adaptive management (learning) benefits

If one concluded that enough is known to make a decision, then that action is taken. If, on the other hand, it was concluded that more information was desired before making a decision (e.g., to better customize the intervention or to have more confidence in the outcome), prioritizing decisions to collect more information might include considering things like:

- The scale of uncertainty (the difference between the information required to make a management decision and the amount of information already possessed)
- The spatial relevance of the information
- The temporal applicability of the information
- Is the information relevant to more than one species?
- Does the information complement, or add value to, other information or decision-support tools?
- The cost to resolve the uncertainty

In many cases these questions will be evaluated qualitatively rather than quantitatively. Expert judgments and subjective assessments will be involved. This is true in all organizations. Nevertheless, the process of making decisions (to act or to collect information) will be improved to the extent that criteria and questions like these can be brought into the process regularly and systematically.

Appendix B. Guidance for Evaluating Progress

1) High. The uncertainty has been resolved in the Basin or elsewhere at least for some focal species and in some geographical areas. For example, the issue is sufficiently addressed in the Basin to make well-informed management decisions for the species studied. Additional information may be needed for species or locations not yet studied.

2) Medium. Additional investigation is warranted if any of the following are true:
    a. Results are not yet convincing, or the scale of information collection is not yet sufficient.
    b. Considerable information has been collected and findings are generally known but data synthesis and reporting has not been completed.
    c. The direction of effect is generally known, but more quantitative assessment is needed to guide decision making.

3) Low. Additional investigation is warranted if any of the following are true:
    a. The uncertainty is new, and little information is available from outside the Basin or from related species.
    b. Much more information gathering and/or analysis are needed to draw initial inferences or to inform management decisions.
    c. Perhaps some information has been gathered, but no initial inference is possible without additional data, analysis, and reporting.

4) Not Investigated. Investigation is warranted if either of the following is true:
    a. No one to our knowledge has investigated or plans to investigate the uncertainty.
    b. No information is available from studies in the Basin or elsewhere to help address the uncertainty.

5) Not assessable. As posed, the uncertainty is intractable or cannot be addressed by research in the foreseeable future.

Appendix C. Guidance for Evaluating Criticality

The ISAB and ISRP reviewers considered these criteria as guidance for ranking the level of criticality of individual uncertainties using a High, Medium, or Low (H-M-L) scale and for describing the rationale for the ranking. Affirmative answers to the questions below correspond to a higher level of criticality.

The 2014 Fish and Wildlife Program lists the following seven criteria (numbered) for prioritizing research uncertainties. The ISAB and ISRP suggest additional bulleted questions as further guidance, expanding on the Council's criteria. Overall, the ability of research to help achieve the goals and objectives of the Fish and Wildlife Program was considered to be the most important criterion.

Goals and objectives criteria

1) Legal relevance — does the uncertainty address the Program's mandate to mitigate, protect, and enhance fish and wildlife affected by the hydrosystem?
2) Program relevance — does it address hypotheses relevant to management decisions (an underlying assumption of the Program) and include expected effectiveness outcomes?
3) Focal species — does it inform activities directed to focal species? If so, it will be ranked higher.

ISAB and ISRP additions:

- Will solving (answering) the uncertainty significantly increase the protection, enhancement and resilience of habitat for focal species?
- Will solving the uncertainty promote abundance, diversity and adaptability, and thus, the survival and resilience of focal species?

Feasibility and applicability criteria

1) Broad applicability — is it likely to have widespread application throughout the Basin?
2) Time required — is it likely to generate conclusions in a reasonable amount of time? (generally considered to be three to five years but may be longer depending on the issue)
3) Statistical validity — is the critical uncertainty answerable in terms of yielding statistically reliable results?

ISAB and ISRP additions:

- Will the scale of the application have a positive effect on focal populations throughout the Basin, and will the effect be sustainable for a reasonable period of time?

- How tractable is the uncertainty? Issues that are more tractable would be rated higher than those that are not.[32]
- Combined with the progress to date on addressing a specific critical uncertainty, will added effort resolve the uncertainty in a reasonable period of time?

Public engagement criterion

Engaging the public will significantly improve stewardship of natural resources targeted for restoration by the Fish and Wildlife Program. Public engagement should, therefore, be included as an important criterion for determining criticality.

- Can the uncertainty be addressed in a manner that will inform and engage the public to improve stewardship of natural resources targeted for restoration by the Program?

Cost criterion

1) Cost – The value of a funded research project should be equal to or higher than its cost. In the case of competing proposals, the least costly research that intends to produce the same information will receive priority. All direct and indirect costs should be considered, including the cost of the proposal to the hydropower system.

The cost criterion is primarily for the Council's policy consideration rather than the ISAB/ISRP's scientific evaluation. Moreover, the ISAB/ISRP do not have the data necessary to consider this criterion, for example, even basic costs such as infrastructure, hydrosystem operational, and ongoing O&M costs. Consequently, the ISAB/ISRP did not explicitly base its criticality determination on this criterion.

[32] While some issues might have a high level of uncertainty because they are difficult to quantify due to technical, scale, or complexity issues, others have high uncertainty because the issue has not been adequately addressed (e.g., an emerging "game-changing" issue, such as climate or contaminants). Having quantitative objectives and measureable outcomes would facilitate evaluation of this criterion.

Appendix D. ISRP and ISAB Comments on Annual Reports for Fish and Wildlife Program Projects with a Research, Monitoring, and Evaluation Work Element

This appendix to Part 2 includes ISRP and ISAB member evaluations of the most recent annual progress reports, submitted on or before May 2015, for 187 ongoing 2015 Fish and Wildlife Program projects that contained a research, monitoring, or evaluation (RME) work element, about half of the approximately 360 Program-funded projects. The annual reports were evaluated to address the Council's question: ***Is ongoing research making progress in answering critical uncertainties in the current [2006] research plan?***

This appendix is over 375 pages and is available online: www.nwcouncil.org/media/7149871/isabisrp2016-1appendixd.pdf.

Literature Cited

Allendorf, F.W., G. Luikart, and S.N. Aitkin. 2013. Conservation and the Genetics of Populations. Second edition. Wiley-Blackwell.

Arismendi, I., M. Safeeq, J.B. Dunham, and S.L. Johnson. 2014. Can air temperature be used to project influences of climate change on stream temperature? Environ. Res. Lett. 9: 1-12.

Arrow, K.J. 1974. The Limits of Organization. Fels Lectures on Public Policy Analysis. W.W. Norton & Company.

Azuma, D.L., B.N.I. Eskelson, and J.L. Thompson. 2014. Effects of rural residential development on forest communities in Oregon and Washington, USA. Forest Ecology and Management 330 (2014): 183-191.

Baker, J.P., D.W. Hulse, S.V. Gregory, D. White, J. Van Sickle, P.A. Berger, D. Dole, and N.H. Schumaker. 2004. Alternative futures for the Willamette river basin. Ecological Applications 14:313–324.

Bakker K. 2012. Water security: Research opportunities and challenges. Science 337: 914-915.

Bateman, Ian J. and 24 others. Bringing ecosystem services into economic decision-making: land use in the United Kingdom. 2013. Science 341.6141: 45-50.

Beckman, B.R., and D.A. Larsen. 2005. Upstream migration of minijack (age-2) Chinook salmon in the Columbia River: behavior, abundance, distribution, and origin. Transactions of the American Fisheries Society 134:1520– 1541.

Bowen, W.D., and D. Lidgard. 2011. Vertebrate predator control: effects on prey populations in terrestrial and aquatic ecosystems. DFO Canada Science Advisory Secretariat Research Document 2011/028: vi + 33p.

Boyce, M.S., and R.L. Byrne. 2007. Managing Predator-Prey Systems: Summary Discussion. Transactions of the 72nd North American Wildlife and Natural Resources Conference 72:19-33.

Boyce, M.S., C.J. Johnson, E.H. Merrill, S.E. Nielsen, E.J. Solberg, and B. van Moorter. 2016. Can habitat selection predict animal abundance? Journal of Animal Ecology 85, 11-20.

BPA/Corps. 2012. Columbia Estuary Ecosystem Restoration Program: 2012 Strategy Report. DRAFT, Bonneville Power Administration and U.S. Army Corps of Engineers, Portland, Oregon.

Bromley, D.W., and M.M. Cernea. 1989. The management of common property natural resources: Some conceptual and operational fallacies. Vol. 57. World Bank Publications. 1989.

Brown, R.S., E.W. Oldenburg, A.G. Seaburg, K.V. Cook, J.R. Skalski, M.B. Eppard, and K.A. Deters. 2013. Survival of seaward-migrating PIT and acoustic-tagged juvenile Chinook salmon in the Snake and Columbia Rivers: an evaluation of length-specific tagging effects. Animal Biotelemetry 1:8. http://www.animalbiotelemetry.com/content/1/1/8

Buhle, E.R., K.K. Holsman, M.D. Scheuerell, and A. Albaugh. 2009. Using an unplanned experiment to evaluate the effects of hatcheries and environmental variation on threatened populations of wild salmon. Biological Conservation 142:2449-2455.

Bunn S.E., E.G. Abal, M.J. Smith, S.C. Choy, C.S. Fellows, B.D. Harch, M.J. Kennard, and F. Sheldon. 2010. Integration of science and monitoring of river ecosystem health to guide investments in catchment protection and rehabilitation. Freshwater Biology 55.s1: 223-240.

Busack, C., C.M. Knudsen, G. Hart, and P. Huffman. 2007. Morphological differences between adult wild first-generation hatchery upper Yakima River spring Chinook. Transactions of the American Fisheries Society 136:1076-1087.

Byrd, K., W. Labiosa, J. Kreitler, M. Gould, and J. Bolte. 2010. The Puget Sound Ecosystem Portfolio Model: A Regional Analysis to Support Restoration Planning. The 3rd USGS Modeling Conference: http://geography.wr.usgs.gov/pugetSound/docs/PSEPM_ModelingConference.pdf

Cao, Y., L. Hinz, B. Metzke, J. Stein, and A. Holtrop. 2015. Modeling and mapping fish abundance across wadeable streams of Illinois, USA based on landscape-level environmental variables Canadian Journal of Fisheries and Aquatic Sciences, *, **-** DOI: 10.1139/cjfas-2015-0343.

Carpenter, S.R., S.W. Chisholm, C.J. Krebs, D.W. Schindler, and R.F. Wright. 1995. Ecosystem Experiments. Science 269: 324-327.

Costa, D.L. and M.E. Kahn. 2003. Civic engagement and community heterogeneity: An economist's perspective. Perspectives on politics 1.01:103-111.

Christiansen H.E., A.C. Mehinto, F. Yu, R.W. Perry, N.D. Denslow, A.G. Maule, M.G. Mesa. 2013. Correlation of gene expression and contaminant concentrations in wild largescale suckers: A field-based study. Sci Total Environ http://dx.doi.org/10.1016/j.scitotenv.2013.08.034

Christie, M.R., M.J. Ford, and M.S. Blouin. 2014. On the reproductive success of early-generation hatchery fish in the wild. Evolutionary Applications 7:883-896.

Christie, M.R., M.L. Marine, R.A. French, R.S. Waples, and M.S. Blouin. 2012. Effective size of a wild salmonid population is greatly reduced by hatchery supplementation. Heredity 109:254-260.

Coleman, A.M., G.E. Johnson, A.B. Borde, H.L. Diefenderfer, N.K. Sather, T.E. Seiple, and J.A. Serkowski. 2013. The Oncor Geodatabase for the Columbia Estuary Ecosystem Restoration Program: Annual Report, 2012. PNNL-22405, final report submitted to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon, by Pacific Northwest National Laboratory, Richland, Washington.

Copeland, T., D.A. Venditti, and B.R. Barnett. 2014. The importance of juvenile migration tactics to adult recruitment in stream-type Chinook salmon populations. Transactions of the American Fisheries Society 143:1460-1475.

Cramer, S.P. and N.K. Ackerman. 2009. Linking stream carrying capacity for salmonids to habitat features. Pages 225-254 in E.E. Knudsen and J.H. Michael Jr. editors. Pacific salmon environmental and life history models: advancing science for sustainable salmon in the future. American Fisheries Society Symposium 71, American Fisheries Society, Bethesda, Maryland.

CSS (Comparative Survival Study). 2015. Comparative survival study of PIT-tagged spring/summer/fall Chinook, summer steelhead, and sockeye: 2015 Annual Report. BPA Project Report 1996-202-00. 486p.

Dalton, M.M., P.W. Mote, A.K. Snover, eds. 2013. Climate change in the Northwest: Implications for our landscapes, waters, and communities. Washington DC: Island Press.

Dekker, D. 2006. Wolf wars. Alberta Naturalist. 36(4):10–15.

Fast, D.E., W.J. Bosch, M.V. Johnston, C.R. Strom, C.M. Knudsen, A.L. Fritts, G.M. Temple, T.N. Pearsons, D.A. Larsen, A.H. Dittman, and D. May. 2015. A Synthesis of findings from an integrated hatchery program after three generations of spawning in the natural environment, North American Journal of Aquaculture 77:3, 377-395.

Faulkner, J.R., S.G. Smith, D.L. Widener, T.M. Marsh, R.W. Zabel. 2015. Survival estimates for the passage of spring-migrating juvenile salmonids through Snake and Columbia River dams and reservoirs, 2014. Report of the National Marine Fisheries Service to the Bonneville Power Administration. Portland, Oregon.

Fausch, K.D., C.E. Torgersen, C.V. Baxter, and H.W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:483-498.

Feist, G.W., M.A. Webb, D.T. Gundersen, E.P. Foster, C.B. Schreck, A.G. Maule, M.S. Fitzpatrick. 2005. Evidence of detrimental effects of environmental contaminants on growth and reproductive physiology of white sturgeon in impounded areas of the Columbia River. Environ Health Perspect 113:1675-1682.

Fraser, D.J. 2008. How well can captive breeding programs conserve biodiversity? A review of salmonids. Evolutionary Applications 1: 535-586.

Finkl, C. W. and C. Makowski. 2014. Remote sensing and modeling: Advances in coastal and marine resources. Springer: New York.

Frankham, R., J.D. Ballou, and D.A. Briscoe. 2010. Introduction to Conservation Genetics. Second edition. Cambridge University Press.

Fresh, K.L. 1997. The role of competition and predation in the decline of Pacific salmon and steelhead. Pages 245-275 in D.J. Stouder, P.A. Bisson, and R.J. editors. Pacific salmon and their ecosystems. Status and future options. Chapman and Hall, New York.

Fritts, A.L., J.L. Scott, and T.N. Pearsons. 2007. The effects of domestication on the relative vulnerability of hatchery and wild origin spring Chinook salmon (Oncorhynchus tshawytscha) to predation. Canadian Journal of Fisheries and Aquatic Sciences 64:813-818.

Galbraith, J.R. 1973. Designing complex organizations. Addison-Wesley Longman Publishing Co., Inc.

Galbreath, P.F., M.A. Bisbee Jr., D.W. Dompier, C.M. Kamphaus, and T.H. Newsome. 2014. Extirpation and tribal reintroduction of coho salmon to the interior Columbia River Basin. Fisheries 39(2):77-87.

Geist, D.R., E.V. Arntzen, C.J. Murray, K.E. McGrath, Y-J. Bott, and T.P. Hanrahan. 2008. Influence of river level on temperature and hydraulic gradients in chum and fall Chinook salmon spawning areas downstream of Bonneville Dam, Columbia River. North American Journal of Fisheries Management 27: 30–41.

Gitzen, R., J.J. Millspaugh, A.B. Cooper, and D.S. Licht. 2012. Design and analysis of long term ecological monitoring studies. Cambridge University Press, England, UK.

Grimm, N.B. and C.L. Redman. 2004. Approaches to the study of urban ecosystems: the case of central Arizona-Phoenix. Urban Ecosystems 7:199-213.

Ham, K.D. and T.N. Pearsons. 2001. A practical approach for containing ecological risks associated with fish stocking programs. Fisheries 26 (4):15-23.

Harding, E.K., D.F. Doak, and J.D. Albertson. 2001. Evaluating the effectiveness of predator control: the non-native red fox as a case study. Conservation Biology 15:4, 1114–22.

Harnish, R.A., G.E. Johnson, G.A. McMichael, M.S. Hughes, and B.D. Ebberts. 2012. Effect of migration pathway on travel time and survival of acoustic-tagged juvenile salmonids in the Columbia River Estuary. Transactions of the American Fisheries Society 141:507-519.

Harnish, R.A., R. Sharma, G.A. McMichael, R.B. Langshaw, and T.N. Pearsons. 2014. Effect of hydroelectric dam operations on the freshwater productivity of a Columbia River fall Chinook salmon population. Canadian Journal of Fisheries and Aquatic Science 71: 602–615.

Hatchery Scientific Review Group, Washington Department of Fish and Wildlife, and Northwest Indian Fisheries Commission. 2004a. Technical Discussion Paper #1: Integrated Hatchery Programs. (Available from www.hatcheryreform.us).

Hatchery Scientific Review Group, Washington Department of Fish and Wildlife, and Northwest Indian Fisheries Commission.2004b. Technical Discussion Paper #2: Segregated Hatchery Programs. (Available from www.hatcheryreform.us).

Hatchery Scientific Review Group (HSRG). 2015. Annual report to Congress on the science of hatcheries, 2015. A report on the application of up-to-date science in the management of salmon and steelhead hatcheries in the Pacific Northwest.

Hatten, J.R., K.F. Tiffan, D.R. Anglin, S.L. Haeseker, J.J. Skalicky, H. Schaller. 2009. A spatial model to assess the effects of hydropower operations on Columbia River fall Chinook salmon spawning habitat. North American Journal of Fisheries Management 29: 1379–1405.

Heal, G., and 11 co-authors. 2004. Genetic diversity and interdependent crop choices in agriculture. Resource and Energy Economics 26:175-184.

Herger, L.G., G.A. Hayslip, and P.T. Leinenbach. 2007. Ecological Condition of Wadeable Streams of the Interior Columbia River Basin. EPA-910-R-07-005. U.S. Environmental Protection Agency, Region 10, Seattle, Washington.

Hinck, J.E., C.J. Schmitt, V.S. Blazer, N.D. Denslow, T.M. Bartish, P.J. Anderson, J.J. Coyle, G.M. Dethloff, and D.E. Tillitt. 2006. Contaminants and biomarker responses in fish from the Columbia River and its tributaries: Spatial and temporal trends. Science of the Total Environment 366:549–578.

Hostetter, N.J., A.F. Evans, F.J. Loge, R.R. O'Connor, B.M. Cramer, D. Fryer, and K. Collis. 2015. The influence of individual fish characteristics on survival and detection: similarities across two species. North American Journal of Fisheries Management 35:1034-1045.

Hoffnagle, T.L., R.W. Carmichael, K.A. Frenyea, and P.J. Keniry. 2008. Run timing, spawn timing, and spawning distribution of hatchery- and natural-origin spring Chinook salmon in the Imnaha River, Oregon. North American Journal of Fisheries Management 28:148-164.

Hulse, D.A., Branscomb, and S.G. Payne. 2004. Envisioning Alternatives: using citizen guidance to map future land and water use. Journal of Ecological Applications 325-341.

Interior Columbia Basin Technical Recovery Team. 2007. Viability criteria for application to interior Columbia Basin salmonid ESUs. Review draft. March 2007.

Isaak, D.J. and B.E. Rieman. 2013. Stream isotherm shifts from climate change and implications for distributions of ectothermic organisms. Global Change Biology 19, 742–751, doi: 10.1111/gcb.12073.

IEAB (Independent Economic Analysis Board). 2010-1. Economic risk associated with the potential establishment of zebra and quagga mussels in the Columbia River Basin. Northwest Power and Conservation Council, Portland, Oregon. IEAB Report 2010-1. Available at http://www.nwcouncil.org/fw/ieab/ieab2010-1/

IEAB (Independent Economic Analysis Board). 2013-1. Cost-effectiveness of fish tagging technologies and programs in the Columbia River Basin. Northwest Power and Conservation Council, Portland, Oregon. IEAB Report 2013-1. Available at http://www.nwcouncil.org/fw/ieab/ieab2013-1/

IEAB (Independent Economic Analysis Board). 2013-2. Economic risk of zebra and quagga mussels in the Columbia River Basin. Northwest Power and Conservation Council, Portland, Oregon. IEAB Report 2013-2. Available at http://www.nwcouncil.org/fw/ieab/ieab2013-2/

ISAB (Independent Scientific Advisory Board). 2003-2. Review of strategies for recovering tributary habitat. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2003-2. Available at http://www.nwcouncil.org/fw/isab/isab2003-2

ISAB (Independent Scientific Advisory Board). 2004-2. Comments on the Pacific Northwest Aquatic Monitoring Partnership's (PNAMP) Draft recommendations for monitoring in subbasin plans. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2004-2. Available at http://www.nwcouncil.org/fw/isrp/isrpisab2004-2/

ISAB (Independent Scientific Advisory Board). 2005-4. Report on harvest management of Columbia River salmon and steelhead. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2005-4. Available at www.nwcouncil.org/fw/isab/isab2005-4/

ISAB (Independent Scientific Advisory Board). 2007-1. ISAB latent mortality report. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2007-1. Available at http://www.nwcouncil.org/fw/isab/isab2007-1/

ISAB (Independent Scientific Advisory Board). 2007-2. Climate change impacts on Columbia River basin fish and wildlife. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2007-2. Available at http://www.nwcouncil.org/fw/isab/isab2007-2

ISAB (Independent Scientific Advisory Board). 2008-4. Non-native species impacts on native salmonids in the Columbia River basin (including recommendations for evaluating the use of non-native fish species in resident fish substitution projects. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2008-4. Available at http://www.nwcouncil.org/fw/isab/isab2008-4/

ISAB (Independent Scientific Advisory Board). 2011-1. Columbia River Food Webs: Developing a broader scientific foundation for fish and wildlife restoration. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2011-1. Available at www.nwcouncil.org/fw/isab/isab2011-1/

ISAB (Independent Scientific Advisory Board). 2011-4. Using a comprehensive landscape approach for more effective conservation and restoration. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2011-4. Available at www.nwcouncil.org/fw/isab/isab2011-4/

ISAB (Independent Scientific Advisory Board). 2012-6. Review of the Columbia estuary ecosystem restoration program. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2012-6. Available at http://www.nwcouncil.org/fw/isab/isab2012-6

ISAB (Independent Scientific Advisory Board). 2013-1. Review of 2009 Fish and Wildlife Program. Northwest Power and Conservation Council, Portland Oregon. ISAB Report 2013-1. Available at http://www.nwcouncil.org/fw/isab/isab2013-1

ISAB (Independent Scientific Advisory Board). 2013-3. Review of the IEAB fish tagging cost effectiveness model. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2013-3. Available at http://www.nwcouncil.org/fw/isab/isab2013-3/

ISAB (Independent Scientific Advisory Board). 2013-5. Review of NOAA Fisheries' life-cycle models of salmonid populations in the interior Columbia River basin (June 28, 2013 Draft). Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2013-5. Available at http://www.nwcouncil.org/fw/isab/isab2013-5/

ISAB (Independent Scientific Advisory Board). 2014-1. ISAB Review of the Expert Regional Technical Group (ERTG) Process for Columbia River Estuary Habitat Restoration. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2014-1. Available at http://www.nwcouncil.org/fw/isab/isab2014-1

ISAB (Independent Scientific Advisory Board). 2015-1. Density dependence and its implications for fish management and restoration programs in the Columbia River. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2015-1. 246pp. Available at www.nwcouncil.org/fw/isab/isab2015-1/

ISAB (Independent Scientific Advisory Board). 2015-2. Review of the Comparative Survival Study (CSS) Draft 2015 Annual Report. Northwest Power and Conservation Council, Portland, Oregon. ISAB Report 2015-2. Available at http://www.nwcouncil.org/fw/isab/isab2015-2/

ISRP (Independent Scientific Review Panel). 2003-13. Review of Draft: "An Ecosystem-Based Restoration Plan with Emphasis on Salmonid Habitats in the Columbia River Estuary" (Draft Estuary Plan Review). Northwest Power and Conservation Council, Portland, Oregon. ISRP Report 2003-13. Available at http://www.nwcouncil.org/fw/isrp/isrp2003-13/

ISRP/ISAB (Independent Scientific Review Panel/Independent Scientific Advisory Board). 2005-15. Monitoring and evaluation of supplementation projects. Northwest Power and Conservation Council, Portland, Oregon. ISRP/ISAB Report 2005-15. Available at http://www.nwcouncil.org/fw/isrp/isrpisab2005-15/

ISRP (Independent Scientific Review Panel). 2008-4. Retrospective Report 2007: Adaptive management in the Columbia River basin. Northwest Power and Conservation Council, Portland, Oregon. ISRP Report 2008-4. Available at http://www.nwcouncil.org/media/32920/isrp2008_4.pdf

ISRP (Independent Scientific Review Panel). 2011-14. Review of the Lower Snake River Compensation Plan's Spring Chinook Program. Northwest Power and Conservation Council, Portland, Oregon. ISRP Report 2011-14. Available at www.nwcouncil.org/media/33264/isrp2011_14.pdf.

ISRP (Independent Scientific Review Panel). 2012-3. ISRP Review of the Ocean Synthesis Report: The Marine Ecology of Juvenile Columbia River Basin Salmonids: A Synthesis of Research 1998-2011. Northwest Power and Conservation Council, Portland, Oregon. ISPR Report 2012-3. Available at http://www.nwcouncil.org/fw/isrp/isrp2012-3/

ISRP (Independent Scientific Review Panel). 2013-3. Review of the Lower Snake River compensation Plan Steelhead Program. Northwest Power and Conservation Council, Portland, Oregon. ISRP Report 2013-3. Available at http://www.nwcouncil.org/fw/isrp/isrp2013-3/

Jackson G.D. 2011. The Development of the Pacific Ocean Shelf Tracking Project within the Decade Long Census of Marine Life. PLoS ONE 6(4): e18999. doi:10.1371/journal.pone.0018999.

Jacobson, K., B. Peterson, M. Trudel, J. Ferguson, C. Morgan, D. Welch, A. Baptista, B. Beckman, R. Brodeur, E. Casillas, R. Emmett, J. Miller, D. Teel, T. Wainwright, L. Weitkamp, J. Zamon, and K. Fresh. 2012. The Marine Ecology of Juvenile Columbia River Basin Salmonids: A Synthesis of Research 1998-2011. Prepared by NOAA Fisheries and partners for the NWPCC. 168p.

Jenni, K., D. Graves, J. Hardiman, J. Hatten, M. Mastin, M. Mesa, J. Montag, T. Nieman, F. Voss and A. Maule. 2014. Identifying stakeholder-relevant climate change impacts: A case study in the Yakima River Basin, Washington, USA. Climatic Change 124: 371-384.

Johnson, G.E., H.L. Diefenderfer, R.M. Thom, G.C. Roegner, B.D. Ebberts, J.R. Skalski, A.B. Borde, E.M. Dawley, A.M. Coleman, D.L. Woodruff, S.A. Breithaupt, A.S. Cameron, C.A. Corbett, E.E, Donley, D.A.

Jay, Y. Ke, K.E. Leffler, C.B. McNeil, C.A. Studebaker, and D. Tagestad. 2012. Evaluation of cumulative ecosystem response to restoration projects in the Lower Columbia River and Estuary, 2010. Final report prepared for U.S. Army Corps of Engineers, Portland District under a Government Order with the U.S. Department of Energy Contract DE-AC05-76RL01830, Pacific Northwest National Laboratory Richland, Washington 99352.

Johnson, G.E., N.K. Sather, A.J. Storch, J. Johnson, J.R. Skalski, D.J. Teel, T. Brewer, A.J. Bryson, E.M. Dawley, D.R. Kuligowski, T. Whitesel, C. Mallette. 2013. Multi-Scale Action Effectiveness Research in the Lower Columbia River and Estuary, 2012. PNNL-22481, final annual report submitted to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon, by Pacific Northwest National Laboratory, Richland, Washington.

Johnson, J., T. Johnson, and T. Copeland. 2012. Defining life histories of precocious male parr, minijack, and jack salmon using scale patterns. Transactions of the American Fisheries Society 141:1545-1556.

Kanno, Y., B.H. Letcher, J.A. Coombs, K.H. Nislow, and A.R. Whiteley. 2014. Linking movement and reproductive history of brook trout to assess habitat connectivity in a heterogeneous stream network. Freshwater Biology 59: 142-154.

Keefer, M.L. and C.C .Caudill. 2012. A review of adult salmon and steelhead straying with an emphasis on Columbia River populations. Technical Report 2012-6 for the U.S. Army Corps of Engineers 86p.

Knudsen, C.M., S.L. Schroder, C.A. Busack, M.V. Johnston, T.N. Pearsons, and C.R. Strom. 2008. Comparison of female reproductive traits and progeny of first-generation hatchery and wild upper Yakima River spring Chinook. Transactions of the American Fisheries Society 137:1433-1445.

Knudsen, C.M., S.L. Schroder, C.A. Busack, M.V. Johnston, T.N. Pearsons, W.J. Bosch, and D.E. Fast. 2006. Comparison of life history traits between first-generation hatchery and wild upper Yakima River spring Chinook salmon. Transactions of the American Fisheries Society 135:1130-1144.

Koenings, J. P. and R.D. Burkett. 1987. Population characteristics of sockeye salmon (Oncorhynchus nerka) smolts relative to temperature regimes, euphotic volume, fry density, and forage base within Alaskan lakes. Pages 216-234 in H.D. Smith, L. Margolis, and C.C. Wood (editors) Sockeye Salmon (Oncorhynchus nerka) Population Biology and Future Management. Canadian Special Publications Fisheries and Aquatic Sciences 96.

Kohler, A.E., P.C. Kusnierz, T. Copeland, D.A. Venditti, L. Denny, J. Gable, B.A. Lewis, R. Kinzer, B. Barnett, and M.S. Wipfli. 2013. Salmon-mediated nutrient flux in selected streams of the Columbia River Basin, USA. Canadian Journal of Fisheries and Aquatic Sciences 70: 502-512.

Kohler, A.E., T.N. Pearsons, J.S. Zendt, M.G. Mesa, C.L. Johnson, and P.J. Connolly. 2012. Nutrient Enrichment with Salmon Carcass Analogs in the Columbia River Basin, USA: A Stream Food Web Analysis. Transactions of the American Fisheries Society 141:802-824s.

Kostow, K. 2009. Factors that contribute to the ecological risks of salmon and steelhead hatchery programs and some mitigating strategies. Reviews in Fish Biology and Fisheries 19:9-31.

Kostow, K. 2011. Strategies for reducing the ecological risks of hatchery programs: case studies from the Pacific Northwest. Environmental Biology of Fishes 94:285-310.

Kostow, K.E. and S. Zhou. 2006. The effect of an introduced summer steelhead hatchery stock on the productivity of a wild winter steelhead population. Transactions of the American Fisheries Society 135:825-841.

Larsen, D.A., B.R. Beckman, C.R. Strom, P.J. Parkins, K.A. Cooper, D.E. Fast, and W.W. Dickhoff. 2006. Growth modulation alters the incidence of early male maturation and physiological development of hatchery-reared spring Chinook salmon: a comparison with wild fish. Transactions of the American Fisheries Society 135:1017–1032.

Larsen, D.A., B.R. Beckman, K.A. Cooper, D. Barrett, M. Johnston, P. Swanson, and W.W. Dickhoff. 2004. Assessment of high rates of precocious male maturation in a spring Chinook salmon supplementation hatchery program. Transactions of the American Fisheries Society 133:98–120.

Lawler, J.J., D.J. Lewis, E. Nelson, A.J. Pantinga, S. Polasky, J.C. Withey, D.P. Helmers, S. Martinnuzzi, D. Pennington, and V.C. Radeloff. 2014. Projected land-use change impacts on ecosystem services in the United States." Proceedings of the National Academy of Sciences 111.20: 7492-7497.

Lawley, V., M. Lewis, K. Clarke, and B. Ostendorf. 2016. Site-based and remote sensing methods for monitoring indicators of vegetation condition: An Australian review. Ecological Indicators 60, 1273-1283.

Lee, K.N. 1994. Compass and gyroscope: integrating science and politics for the environment. Island Press.

Lessard, R.B., S. Martell, C.J. Walters, T.E. Essington, and J.F.K. Kitchell. 2005. Should ecosystem management involve active control of species abundances? Journal 10: 1. online: http://www.ecologyandsociety.org/vol10/iss2/art1/

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

Levin, P.S., R.W. Zabel, and J.G. Williams. 2001. The road to extinction is paved with good intentions: negative association of fish hatcheries with threatened salmon. Proceedings of the Royal Society London, B. 268:1153-1158.

Levin, S. and 16 others. 2013. Social-ecological systems as complex adaptive systems: modeling and policy implications. *Environment and Development Economics* 18:111-132.

Loxterman, J.L., and E.R. Keeley. 2012. Watershed boundaries and geographic isolation: patterns of diversification in cutthroat trout from western North America. Bmc Evolutionary Biology, 12:38.

Maas-Hebner, K.G., M.J. Harte, N. Molina, R.M. Hughes, C. Schreck, and J.A. Yeakley. 2015. Combining and aggregating environmental data for status and trend assessments: challenges and approaches. Environmental Monitoring and Assessment 187, 278.

MacKenzie, D. 2005. Occupancy estimation and modeling: inferring patterns and dynamics of species occurrence. Elsevier.

Mantua, N., I. Tohver, and A. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Climatic Change 102:187-223.

McMichael, G.A., M.B. Eppard, T.J. Carlson, J.A. Carter, B.D. Ebberts, R.S. Brown, M. Weiland, G.R. Ploskey, R.A. Harnish, and Z.D. Deng. 2010. The Juvenile Salmon Acoustic Telemetry System: A New Tool. Fisheries 35, 9-22.

Meyer, K.A., B. High, and F.S. Elle. 2012. Effects of stocking catchable-sized hatchery rainbow trout on wild rainbow trout abundance, survival, growth, and recruitment. Transactions of the American Fisheries Society 141:224-237.

Mobrand, L.E., J. Barr, L. Blankenship, D.E. Compton, T.T.P. Evelyn, T.A. Flagg, C.V.W. Mahnken, L.W. Seeb, P.R. Seidel, and W.W. Smoker. 2005. Hatchery reform in Washington State: principles and emerging issues. Fisheries 30:11-23.

Montag, J.M., K. Swan, T. Nieman, J. Hatten, M. Mesa, D. Graves, F. Voss, M. Mastin, J. Hardiman, and A. Maule. 2014. Climate change and Yakama Nation tribal well-being. Climatic Change 124 385-398.

Naish, K.A., J.E. Taylor, P.S. Levin, T.P. Quinn, J.R. Winton, D. Huppert, and R. Hilborn. 2008. An evaluation of the effects of conservation and fishery enhancement hatcheries on wild populations of salmon. Advances in Marine Biology 53:61-194.

Naiman, R.J. 2013. Socio-ecological complexity and the restoration of river ecosystems. Inland Waters 3.4: 391-410.

Naiman, R.J., R.E. Bilby, D.E. Schindler, and J.M. Helfield. 2002. Pacific salmon, nutrients, and the dynamics of freshwater and riparian ecosystems. Ecosystems 399-417.

Naman, S.W. and C.S. Sharpe. 2011. Predation by hatchery yearling salmonids on wild subyearling salmonids in the freshwater environment: a review of the studies, two case histories, and implication for management. Environmental Biology of Fishes 94:21-28.

National Research Council. 2004. Managing the Columbia River: Instream Flows, Water Withdrawals, and Salmon Survival. The National Academies Press: Washington, DC.

Newig, J., and O. Fritsch. 2008. Environmental governance: participatory, multi-level-and effective? No. 15/2008. UFZ Diskussionspapiere.

NOAA Fisheries. 2014. Endangered Species Act Section 7(a)(2) Supplemental Biological Opinion. NOAA's National Marine Fisheries Service. Northwest Region, Portland, Oregon. NWR-2013-9562. http://www.westcoast.fisheries.noaa.gov/publications/hydropower/fcrps/2014_supplemental_fcrps_biop_final.pdf

Northwest Power and Conservation Council. 2006-3. Columbia River Basin Research Plan. Northwest Power and Conservation Council, Portland, Oregon. Council document 2006-3. Available at http://www.nwcouncil.org/media/29261/2006_3.pdf

Northwest Power and Conservation Council. 2014-12. 2014 Columbia River Basin Fish and Wildlife Program. Northwest Power and Conservation Council, Portland, Oregon. Council document 2014-12. Available at http://www.nwcouncil.org/fw/program/2014-12/program/

Olsen, T., T. Kincaid, M. Weber, R. Hill, and S. Leibowitz. 2015. National Aquatic Resource Surveys: Use of Geospatial data in their design and spatial prediction at non-monitored locations. JSM, Seattle, WA, August 08 - 13, 2015.

Ostrom, E. 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press, New York.

Ostrom, E. 2009. Beyond Markets and States: Polycentric Governance of Complex Economic Systems [Nobel Prize lecture]. Stockholm, Sweden: Nobel Media (8 December 2009).

Ostrom, E. 2014. Collective action and the evolution of social norms. Journal of Natural Resources Policy Research 6.4:235-252.

Patton, D.R. 2011. Forest wildlife ecology and habitat management. CRC Press, Boca Raton.

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.

Pearsons, T.N., A.L. Fritts, and J.L. Scott. 2007. The effects of hatchery domestication on competitive dominance of juvenile spring Chinook salmon (Oncorhynchus tshawytscha). Canadian Journal of Fisheries and Aquatic Sciences 64:803-812.

Pearsons, T.N., G.A. McMichael, K.D. Ham, E.L. Bartrand, A.L. Fritts, and C.W. Hopley. 1998. Yakima species interactions studies progress report 1995-1997. Submitted to Bonneville Power Administration, Portland, Oregon (DOE/BP 64878-6).

Pettorelli, N., K. Safi, and W. Turner. 2014. Satellite remote sensing, biodiversity research and conservation of the future. Philos Trans R Soc Lond B Sci. 369, 1643.

Poirier, J.M., T.A. Whitesel, and J.R. Johnson. 2012. Chum salmon spawning activity in tributaries below Bonneville dam: The relationship with tailwater elevation and seasonal precipitation River Research and Applications 28, 882-892.

Rabotyagov, S.S., T.D. Campbell, M. White, J.G. Arnold, J. Atwood, M.L. Norfleet, C.L. Kling, P.W. Gassman, A. Valcu, J. Richardson, R.E. Turner, and N.N. Rabalais. 2014. Cost-effective targeting of conservation investments to reduce the northern Gulf of Mexico hypoxic zone. Proceedings of the National Academy of Sciences 111.52:18530-18535.

Radeloff, V.C., E. Nelson, A.J. Plantinga, D.J. Lewis, D. Helmers, J.J. Lawler, J.C. Withey, F. Beaudry, S. Martinuzzi, V. Butsic, E. Lonsdorf, D. White, and S. Polasky. 2012. Economic-based projections of future land use in the conterminous United States under alternative policy scenarios. Ecological Applications 22:1036-1049.

Rand, P.S., B.A. Berejikian, A. Bidlack, D. Bottom, J. Gardner, M. Kaeriyama, R. Lincoln, M. Nagata, T.N. Pearsons, M. Schmidt, W.W. Smoker, L. A. Weitkamp, and L.A. Zhivotovsky. 2012. Ecological interactions between wild and hatchery salmonids and key recommendations for research and management actions in selected regions of the North Pacific. Environmental Biology of Fishes 94:343-358.

Reed, D.H. and R. Frankham. 2003. Correlation between fitness and genetic diversity. Conservation Biology 17:230-237.

Rieman, B.E., D. l. Isaak, S. Adams, D. Horan, D. Nagel, C. Luce and D. Myers. 2007. Anticipated climate warming effects on bull trout habitats and populations across the interior Columbia River Basin. Transactions of the American Fisheries Society 136:6, 1552-1565.

Roni, P., T. Bennett , R. Holland , G. Pess , K. Hanson , R. Moses , M. McHenry , W. Ehinger, and J. Walter. 2012. Factors Affecting Migration Timing, Growth, and Survival of Juvenile Coho Salmon in Two Coastal Washington Watersheds. Transactions of the American Fisheries Society 141:4, 890-906, DOI: 10.1080/00028487.2012.675895.

Roni, P., T. Beechie, C. Jordan and G. Pess. 2015. Basin scale monitoring of river restoration: Recommendations from case studies in the Pacific Northwest, USA. Pages x-x in N. Fisher, C.A. Rose, P. LeBlanc, and B. Sadler, eds. Managing the Impacts of Human Activities on Fish Habitat: the Governance, Practices, and Science. American Fisheries Society Symposium 78. American Fisheries Society, Bethesda, Maryland.

Rowe, G., and L.J. Frewer. 2005. A typology of public engagement mechanisms. Science, technology & human values 30.2:251-290.

Rowe, G., T. Horlick-Jones, J. Walls, and N. Pidgeon. 2005. Difficulties in evaluating public engagement initiatives: reflections on an evaluation of the UK GM Nation public debate about transgenic crops. Public Understanding of Science 14.4:331-352.

Ruggerone, G.T., B.A. Agler, and J.L. Nielsen. 2011. Evidence for competition at sea between Norton Sound chum salmon and Asian hatchery chum salmon. Environmental Biology of Fishes 94:149-163.

Salathé, E.P., Y. Zhang, L.R. Leung, and Y. Qian, 2010: Regional Climate Model Projections for the State of Washington. Climatic Change 102(1-2): 51-75, doi: 10.1007/s10584-010-9849-y.

Sanderson, B.L., K.A. Barnas, and A.M. Wargo Rub. 2009. Nonindigenous species of the Pacific Northwest: an overlooked risk to endangered salmon? BioScience 59:245-256.

Sarker, A., H. Ross, and K.K. Shrestha. A common-pool resource approach for water quality management: An Australian case study. Ecological Economics 68.1 (2008):461-471.

Scheuerell, M.D., E.R. Buhle, B.X. Semmens, M.J. Ford, T. Cooney, and R.W. Carmichael. 2015. Analyzing large-scale conservation interventions with Bayesian hierarchical models: a case study of supplementing threatened Pacific salmon. Ecology and Evolution 5:2115-2125.

Scheuerell, M.D., R.W. Zabel, and B.P. Sandford. 2009. Relating juvenile migration timing and survival to adulthood in two species of threatened Pacific salmon (Oncorhynchus spp.). Journal of Applied Ecology 46:983-990.

Shortreed, K.S., J.M.B. Hume, and J.G. Stockner. 2000. Using photosynthetic rates to estimate the juvenile sockeye salmon rearing capacity of British Columbia lakes, p. 505- 521. In E.E. Knudsen, C.R. Steward, D.D. MacDonald, J.E. Williams, and D.W. Reiser [eds.]. Sustainable Fisheries Management: Pacific Salmon. CRC Press LLC, Boca Raton, New York.

Sloan, C.A., B.F. Anulacion, J.L. Bolton, D. Boyd, O.P. Olson, S.Y. Sol, G.M. Ylitalo, L.L. Johnson. 2010. Polybrominated Diphenyl Ethers in Outmigrant Juvenile Chinook Salmon from the Lower Columbia River and Estuary and Puget Sound. WA. Archives of Environmental Contamination and Toxicology 58:403-414.

Smith, S.G., D.M. Marsh, R.L. Emmett, W.D. Muir, and R.W. Zabel. 2013. A Study to Determine Seasonal Effects of Transporting Fish from the Snake River to Optimize a Transportation Strategy. Northwest Fisheries Science Center.

Snow, C.G., A.R. Murdoch, and T.H. Kahler. 2013. Ecological and demographic costs of releasing non-migratory juvenile hatchery steelhead in the Methow River, Washington. North American Journal of Fisheries Management 33:1100-1112.

Steinitz, C.L., H. Arias, S. Bassett, M. Flaxman, T. Goode, T. Maddock, D. Mouat, R. Peiser, and A. Shearer. 2003. Alternative futures for changing landscapes: the upper San Pedro River Basin in Arizona and Sonora. Island Press 200p.

Stone, W.W., C.G. Crawford, and R.J. Gilliom. 2013. Watershed Regressions for Pesticides (WARP) Models for predicting stream concentrations of multiple pesticides. Journal of Environmental Quality 42.6. https://dl.sciencesocieties.org/publications/jeq/abstracts/42/6/1838

Tetra Tech. 1996. Lower Columbia River bi-state program—the health of the river, 1990-1996. Integrated Technical Report 0253-01. Redmond, Washington, USA. (C7)

Tirole, J. 1986. Hierarchies and bureaucracies: On the role of collusion in organizations. Journal of Law, Economics & Organization 181-214.

US EPA. 2010. Columbia River Basin Toxics Reduction Action Plan. http://www.epa.gov/columbiariver/columbia-river-basin-toxics-reduction-action-plan-september-2010

US EPA. 2014. Columbia River Strategy for Measuring, Documenting and Reducing Chemicals of Emerging Concern. http://www.epa.gov/columbiariver/columbia-river-strategy-measuring-documenting-and-reducing-chemicals-emerging-concern

US versus Oregon. 2008. 2008-2017 *US versus Oregon* Management Agreement. May 2008.

Walker, B. and D. Salt. 2006. Resilience Thinking: Sustaining Ecosystems and People in a Changing World. Island Press, Washington.

Walters, A.W., T. Copeland, and D.A. Venditti. 2013. The density dilemma: limitations on juvenile production in threatened salmon populations. Ecology of Freshwater Fish 22:508-519.

Wargo Rub, A.M., L. Gilbreath, D. Teel, B. Sandford, and L. Charlton. 2014. Estimation of survival and run timing of adult spring/summer Chinook salmon from the Columbia River Estuary to Bonneville Dam: a cooperative effort between NOAA Fisheries and Columbia River commercial fishermen. Presentation of unpublished results to the Northwest Power and Conservation Council, Portland, OR (November 4, 2014). Available at www.nwcouncil.org/media/7148426/f1.pdf Accessed 2015-01-22.

Waters, C.D., J.J. Hard, M.S.O. Brieuc, D.E. Fast, K.J. Warheit, R.S. Waples, C.M. Knudsen, W.J. Bosch, and K.A. Naish. 2015. Effectiveness of managed gene-flow in reducing genetic divergence associated with captive breeding. Evolutionary Applications 8:956-971.

Weitkamp, L.A., D.J. Teel, M. Liermann, S.A. Hinton, D.M. Van Doornik, P.J. Bentley. 2015. Stock-specific size and timing at ocean entry of Columbia River juvenile Chinook salmon and steelhead: implications for early ocean growth. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 7:370-392. http://dx.doi.org/10.1080/19425120.2015.1047476

Wenger, S.J., D.J. Isaak, J.B. Dunham, K.D. Fausch, C.H. Luce, H.M. Neville, B.E. Rieman, M.K. Young, D.E. Nagel, D.L. Horan, and G.L. Chandler. 2011. Role of climate and invasive species in structuring trout distributions in the interior Columbia River Basin, USA. Can. J. Fish. Aquat. Sci. 68: 988–1008.

Willamette River Basin Atlas, 2002. Oregon State University Press. http://osupress.oregonstate.edu/book/willamette-river-basin-atlas

Willamette Water 2100. http://water.oregonstate.edu/ww2100/

Williamson, K.S., A.R. Murdoch, T.N. Pearsons, E.J. Ward, and M.J. Ford. 2010. Factors influencing the relative fitness of hatchery and wild spring Chinook salmon (Oncorhynchus tshawytscha) in the Wenatchee River, Washington, USA. Canadian Journal of Fisheries and Aquatic Sciences 67:1840-1851.

Wu, H., J.S. Kimball, M.M. Elsner, N. Mantua, R.F. Adler, and J. Stanford. 2012. Projected climate change impacts on the hydrology and temperature of Pacific Northwest Rivers. Water Resources Research 48:WI 1530.

Yodzis, P., 2001. Culling predators to protect fisheries: a case of accumulating uncertainties-response. Trends Ecol. Evol. 16, 282–283.

Zabel, R. and T. Cooney. 2013. Recruits-per-spawner in base versus current time periods—do they differ? Appendix C of the 2014 FCRPS Supplemental Biological Opinion NOAA Fisheries.