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10. Decision Support Models as Tools for Developing Management Strategies: Examples from the Columbia River Basin

THE INDEPENDENT SCIENTIFIC ADVISORY BOARD[1]

Abstract.–We examine decision-support models designed to help recover salmon *Oncorhynchus* spp. in the Columbia River Basin as a case study for the use of models to help resolve scientific uncertainty and select management options. The models all have somewhat different objectives, use different data, and deal with a variety of salmon-related issues. Divergence of model outputs has, in the past, been used to justify different policy positions, leading some to conclude that science has failed to provide clarity to salmon recovery planning. Three distinct approaches are represented in the models: decision analysis, statistical, and expert system. Of the three approaches, decision analysis provides the clearest management advice and the most formal method for treating uncertainty. Its success depends on the engagement of decision makers in framing questions, identifying management options under consideration, and assigning values to possible outcomes. However, decision analysis could be very difficult to perform. As an alternative, the statistical model is the traditional scientific approach and it can operate with a large degree of detachment from policy. Statistical models proceed by testing hypotheses and estimating life-cycle parameters with available data. They have the advantage of scientific clarity, rigor, and empirical objectivity. The limitation of a statistical model is that the scope of the questions and their answers are restricted by availability of data, and in a domain that is data-poor, many pressing questions go unanswered. Expert system approaches fill gaps in data with expert opinion. In the context of salmon recovery, expert opinion allows consideration of the most concrete menu of specific options for salmon management. Expert opinion is a weaker basis for scientific prediction than is a mathematical relationship validated with empirical data. However, at the level of spatial resolution and environmental detail required to make salmon management decisions affecting the entire Columbia River Basin, there are no validated mathematical formulae for predicting the effects of management actions on salmon, and no adequate data archive exists for deriving such relationships. Communication between scientists and managers is improved when there is a formal institutional mechanism for summarizing scientific results and clarifying the interpretation of models for policy makers. If a

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modeling effort is driven by a desire to contribute to a particular decision, it is helpful to initially invest in enough communication to ensure that the model really is addressing the right question. Scientists can help managers craft decision rules that are formalized *before* analyses are undertaken. Decision rules define what measurements will be made, what statistical operations will be performed, and what threshold magnitudes of estimated quantities at specified levels of certainty will serve as criteria for the decision. Such specifications ensure that model results are properly used in the decision process. Committing to these specifications in advance helps dispel suspicions that analyses may be manipulated to achieve a particular outcome.

Introduction

The Columbia River Basin was once one of the most productive river systems for Pacific salmon *Oncorhynchus* spp. on the Pacific coast of North America. Estimates of the number of adult salmon entering the Columbia River prior to development range from 7 to 16 million (Chapman 1986; Northwest Power Planning Council 1986). Between the mid-1800s and the late 1900s, the total number of salmon declined to approximately one-eighth of the pre-development run sizes although yearly totals have been highly variable. Declines of some of the runs have reached the point that populations are listed as threatened or endangered under the federal Endangered Species Act (ESA; Table 1). Concern for the continued loss of salmon in the Columbia River Basin has resulted in one of the largest, most administratively complex, and expensive fishery restoration programs in the world (Volkman and Lee 1994; National Research Council 1996).

Prior to water impoundment, over 422,000 km^2 of the Columbia River Basin's area, 673,000 km^2, were available to salmon, but only 189,000 km^2 remain available today. This reduction amounts to a 55% loss of total watershed area and a 31% loss of stream area (National Research Council 1996). By 1975, when dam construction in the Columbia Basin was essentially complete, 58 dams had been built for hydropower development and an additional 78 had been built for multiple uses (hydropower, flood control, water storage, recreation), including 14 mainstem Columbia River and 13 mainstem Snake River dams. Only a single 80-km reach of the mainstem Columbia River near the Hanford Nuclear Reservation—between McNary Reservoir and Priest Rapids Dam—and

TABLE 1.–Listing status of Columbia River salmon under the federal Endangered Species Act as of early 2002. ESU refers to Evolutionarily Significant Unit, a distinct population segment recognized by the National Marine Fisheries Service.

Species	ESU	Status
Sockeye (*Oncorhynchus nerka*)	Snake River	Endangered
Chinook (*O. tshawytscha*)	Snake River fall	Threatened
	Snake River spring/summer	Threatened
	Upper Columbia River spring	Endangered
	Lower Columbia River spring/fall	Threatened
	Upper Willamette River spring	Threatened
Chum (*O. keta*)	Columbia River	Threatened
Coho (*O. kisutch*)	Lower Columbia River	Candidate
Steelhead (*O. mykiss*)	Snake River	Threatened
	Upper Columbia River	Endangered
	Middle Columbia River	Threatened
	Lower Columbia River	Threatened
	Upper Willamette River	Threatened

the reach from Bonneville Dam to the river's mouth currently remain unimpounded within the range of Pacific salmon.

Although declines of Pacific salmon and the widespread extent of habitat loss are well known, the Columbia River Basin suffers from a shortage of scientific information. So serious has this lack of information been that Naiman et al. (1995) states:

> More than $150 million is spent annually on the recovery of the degraded salmon and steelhead runs in the Columbia River, yet a monitoring program that would enable the measurement of the major sources of mortality at key points in the river and ocean ecosystem does not exist. With little or no formal peer review, this spending constitutes twice the annual budget of the Environmental Biology Program at the National Science Foundation, which is the primary source of competitive funding for basic research in freshwater ecology in the United States.

The popular press has suggested that Columbia Basin salmon management constitutes a hugely expensive "failure" of "salmon science." We will not comment here on the difficult and inflammatory question of whether the recovery effort, to date, should be judged a failure. We take this opportunity, however, to correct a misperception about the role of science in the recovery effort. Put most simply, the conventionally cited huge amounts of money spent on the recovery effort were not spent on "salmon science." The bulk of the money was spent, and continues to be spent, on management actions. Historically, the role of science in the process has not been large. Some management actions have lacked a strong scientific basis, and results of many actions have not been monitored with enough thoroughness to determine their effect.

Policy makers in the Columbia Basin know that planning, coordinating, and implementing salmon recovery actions will require improved incorporation of scientific information into restoration strategies. They also know there are many data gaps and that decision support tools (models) will have to accommodate considerable uncertainty (Chapter 9, this volume). Similar predicaments are surely faced by restoration managers in similar situations elsewhere; decisions involving large budgets and contentious project priorities must be made with incomplete data.

With the goal of improving integration of scientific information into restoration policies in the Columbia Basin, various decision-support models were developed to aid in management planning. While these models were specific to salmon in the Columbia River basin, their approaches represent a cross-section of the types of decision-support systems available today; therefore, understanding their strengths and limitations is useful.

Major analytical efforts supporting decision making for salmon restoration in the Columbia Basin include the following:

1. *Cumulative Risk Initiative* (CRI), the National Marine Fisheries Service's model for predicting trends and risks to salmon populations;
2. *Plan for Analysis and Testing Hypotheses* (PATH), a multi-organization's (state, federal agencies, and tribes) fish survival modeling effort which actually included several models:
   - *Fish Leaving Under Several Hypotheses* (PATH-FLUSH),
   - *Columbia River Salmon Passage* (PATH-CRiSP), and
   - *Ecosystem Management* (PATH-EM);
3. *Ecosystem Diagnosis and Treatment* (EDT), the Northwest Power Planning Council's habitat assessment model;
4. *Interior Columbia River Basin Ecosystem Management Plan* (ICBEMP-BBN), the U.S. Forest Service and Bureau of Land Management's Bayesian Belief Network analysis of salmon viability; and

5. COHORT, the Columbia River Intertribal Fish Commission's (CRITFC) model of salmon population dynamics.

Objectives of each model differed. The CRI model (Kareiva et al. 2000) was developed to help predict population trends in response to different types of salmon recovery actions. As the lead agency in the salmon listing and recovery process under the ESA, the National Marine Fisheries Service used CRI as a diagnostic tool to evaluate management options and determine extinction risk. The three PATH models (Deriso et al. 2001; Peters and Marmorek 2001; Peters et al. 2001) were focused primarily on modeling survival of juvenile and adult salmon as they migrated through the mainstem Columbia and Snake rivers. These models were to assist in evaluating different management actions related to operation of the Columbia hydroelectric system, including reducing smolt mortality through turbines and other passage routes, barging smolts around dams, and reservoir drawdown. The EDT model (Mobrand et al. 1997) has been used to evaluate the relative importance of different environmental factors at various points along the salmon (or bull trout *Salvelinus confluentus*) life cycle, and also serves as a basis for prioritizing habitat restoration activities in each of the Columbia River's 62 subbasins. The ICBEMP-BBN model (Quigley and Arbelbeide 1997) was developed to evaluate the probability of maintaining well-distributed, interconnected habitats and salmon and other fish populations over broad areas of federal management—U.S. Forest Service and Bureau of Land Management forests and rangelands. Finally, the COHORT model was developed by the Columbia River Intertribal Fish Commission to assist some Native American tribes in the Columbia Basin in determining the efficacy of different restoration alternatives and in forecasting the number of salmon that could be harvested according to treaty rights.

The outcomes of models have played, and will continue to play, a role in the decision-making process. However, when objectives, data categories, and assumptions vary among the models, it is not surprising that conclusions differ. Decision making is hampered when scientific assessment and synthesis becomes engulfed in a collision of models, with interest groups and agencies advocating conclusions that best support their interests and mandates. Such debates will undoubtedly occur in the Columbia Basin and elsewhere as an inevitable consequence of the gravity and implications of impending decisions, and the lack of credible scientific conclusions concerning the feasibility of outcomes following any particular management action.

We believe decision makers are well served by drawing on all available analytical tools, as well as by focusing on areas of consensus among the models or the weight of evidence provided collectively by them. Because the Columbia Basin is typical of other large river basins throughout the world, our analysis of the decision-support models for salmon recovery in the basin may help avoid a collision of models here and elsewhere. Our objective is not to review the models in detail or to determine how well they achieved their stated goals, but rather to illustrate how different modeling techniques were used to address different problems. The review of these decision-support tools was conducted in 2000 and 2001. Since then, the structure of some of the models has changed; however, the following discussion represents our assessment of their objectives and approach prior to this change.

Modeling Approaches

The PATH-FLUSH and PATH-CRiSP models were primarily designed only to evaluate Snake River salmon recovery actions, including breaching the lower four Snake River dams, increasing transportation of juveniles around dams, and reducing harvest of adults (Chapter 9, this volume). The ICBEMP-BBN and EDT models were primarily designed to evaluate large-scale habitat management alternatives across the landscape of the Columbia River Basin. The remaining models—CRITFC, CRI, and PATH-EM—were used to predict trends in salmonid populations based on counts of fish and rates of change in population parameters.

There were three distinct approaches represented in the models available for decision support in Columbia Basin salmon management:

1. *decision analysis*, embodied most clearly in PATH,
2. *statistical*, embodied most clearly in CRI, and
3. *expert system*, embodied most clearly in ICBEMP-BBN and EDT.

The actual models were not pure manifestations of the respective approaches, but each model did rely more heavily on one approach than others. Of the three approaches, the PATH decision analysis is most closely directed at providing management advice, and it is formal about factoring uncertainty into the analysis. This modeling approach, if successful, has the potential to be very useful to decision makers. The decision analysis approach, however, is very difficult to implement successfully. Its success depends crucially on the engagement of the actual decision makers in framing the questions about salmon ecology that need to be answered, identifying the management options that are under consideration, and defining the values placed on the possible outcomes. The decision analysis approach also requires clear communication between the technical analysts and the decision makers, including communication about complicated matters of risk, probability, and uncertainty. Such engagement and communication is often difficult to achieve in the complex institutional setting of Columbia Basin salmon management where there is so much fragmentation of decision-making authority (Lee 1993).

The statistical approach is scientifically the most classical of the three and can operate with a large degree of detachment from policy. It proceeds by testing hypotheses (i.e., evaluating the strength of relationships between salmon and their environment, and estimating life-history parameters with available data). This has the advantages of clarity, rigor, and empirical objectivity. The limitation of the statistical approach is that the scope of the questions that can be answered with satisfactory conclusiveness is restricted by the availability of data. In a domain that is data-poor, many pressing questions may go unanswered. This approach may be scientifically sound, but it often does not fully address the needs of the managers who recognize gaps in information.

Expert-system approaches fill gaps in empirical data with heuristic information, local knowledge, and expert opinion. In the context of salmon recovery, expert opinion allows consideration of the most concrete menu of specific options for actual management. This broader approach to information capture is, admittedly, a weaker basis for scientific prediction than is a mathematical relationship validated with an archive of quantitative empirical data. But at the level of spatial resolution and environmental detail required to make salmon management decisions, no available validated mathematical equations are available for predicting reliably the effects of management actions on salmon, and no adequate data archive exists for deriving such equations.

In this light, the expert-system approach may well be a reasonable and practical method for providing tentative answers to some management questions that do need to be addressed quickly. There is often a pressing need to make very specific assessments about a broad spectrum of possible management interventions, to decide which interventions are worth trying, and to decide where and on what scale they should be implemented. Clearly, however, the tentativeness of answers from expert systems should be kept in mind when these answers are factored into management decisions.

Models and Uncertainty in Restoration Management

When decisions must be made in the face of significant uncertainty, there are valid uses for hard data and speculative information. In the short term, speculative information is the only option for filling data gaps. These two kinds of information should serve different roles in the decision process, but things often go badly if those roles get confused. Basically, speculative information generates hypotheses whereas hard data (i.e., secure scientific information) is accumulated through careful testing of hypotheses and estimation of critical life-history parameters through long-term monitoring. The two can work together if hypotheses and estimates are used as a basis for designing and implementing management experiments. Monitoring the results of these experiments then provides data to test the hypotheses or estimate new parameters. In this way, expert system and statistical approaches can be complementary, and decision analysis can optimize the mix. Prudence demands that management experiments be performed on such a scale that we can afford the consequences of any probable outcome (Walters 1986). The contribution of decision analysis is in the balancing of the prospects for each experiment—the value of desired outcomes, the costs of undesired outcomes, and the value of secure information that will be obtained in either case.

For decision makers to accept scientific advice on the merits of experimental management, the nature and extent of the uncertainties should be explained in language that is realistic and vivid. It is not a matter of attempting to teach the decision makers to like uncertainty—why should anyone do that? The key message is learning to cope with unavoidable uncertainty. This is especially important when the uncertainty is large, as is common in environmental problems.

Ideally, decision-support models for river restoration constitute a way of organizing and communicating information. When modeling is done thoughtfully, it provides a systematic and objective way of identifying what we can and cannot predict reliably about the behavior of aquatic ecosystems. When the predictive power is relatively slight, as is the case when models are applied to many of the current salmon management questions in the Columbia River basin, a good model serves the very important roles of generating hypotheses and pinpointing crucial gaps in information. Knowledge of information gaps provides a valuable guide for setting priorities for new data collection and it suggests new experiments to test hypotheses. Ecological models also provide a means for examining the combined implications of sets of assumptions about mechanisms and sets of measurements on the system of interest. The motivation for this exercise may vary.

The motivation is often quite different in academic and management contexts. In an academic setting, the greatest interest usually centers on use of models to test assumptions in order to gauge the current state of theoretical understanding. This is generally carried out by quantifying indices of internal consistency between the data and relationships implicit in the assumed mechanisms. Often, the goal will be to compare alternative sets of assumptions to see which are more likely to be true. These academic uses of models are tolerant of very large discrepancies between models and reality. Models, by design, are often highly idealized in order to shed light on particular mechanisms of interest whereas reality is expected to be far more complicated. This mismatch is treated as "noise" that can be generally ignored provided it is not so large as to obscure the contrast between alternative sets of assumptions.

In management settings, the greatest interest usually centers on using models to make predictions about the consequences of alternative management actions under consideration. Here it is taken for granted that models are an approximation, probably an oversimplification of reality, and actual outcomes will not exactly match model predictions. As Lee (1993, p. 61) states, "The behavior of natural systems is incompletely understood. Predictions of behavior are accordingly incomplete and often incorrect. These facts do not decrease the value of models, but they do make it clear that ecosystem models are not at all like engineering models of bridges or oil refineries." But the consequences of an ecological decision result in real outcomes, and for this reason discrepancies between models and reality are of crucial concern. Owing to limitations of our theoretical knowledge and limitations of available data, these discrepancies may be large and unavoidable. Because model predictions become a basis for salmon management decisions, the discrepancies between models and reality cannot just be dismissed as noise. Discrepancies require careful analysis to reveal the uncertainty of the predictions.

The point of uncertainty analysis for decision-support models is twofold. One goal is to reduce the uncertainty to the extent feasible even if this is achieved at the expense of loss of elegance (simplicity) or loss of a clear relationship to academic theories. The second and somewhat less obvious goal is to characterize and, if possible, quantify the uncertainty to provide a rational basis for hedging bets and setting margins of error for predictions in a decision process.

Quantification of uncertainty in ecosystem models may be based on probabilities that are normally derived by statistical procedures. For example, if we know that an ecological prediction is always 10% too high, we simply adjust our prediction accordingly. Uncertainty is concerned with the component of the discrepancy between prediction and actual performance that is not so consistent. In other words, uncertainty characterization is concerned with determining the probability that the prediction error will be high, or low, by any stated amount. In technical shorthand, uncertainty can be communicated in terms of the mean or variance of a mathematically defined probability distribution.

Models, Science, and Policy

For scientific results to enable management decisions that are effective in accomplishing societal goals (e.g., ecological and economic) for river restoration, there should be not only a belief by decision makers in the credibility of the science and its relevance to the problems being addressed, but also effective communication between scientists and decision makers so that the latter are well informed of the consequences of management alternatives. Each modeling approach has something useful to offer policy makers provided they understand the associated logic, supporting evidence, limitations, and assumptions. Without that understanding, managers may be tempted to use modeling results in superficial and spurious ways that can add confusion to deliberations. Such misuse or misunderstanding has the potential to create an atmosphere that undermines science.

The decision-support models we reviewed were developed to address the specific needs of salmon or habitat management organizations. In all cases the models were of greatest utility to the sponsoring organization. Several of the models—EDT, ICBEMP-BBN, and CRI—received considerable support from their respective sponsors. The decision-making authority was part of the same organization that had ownership in the model, and scientists developing the models belonged to the organization. Decision questions that the modeling efforts were intended to answer were well defined in advance of the modeling project, the efforts were directed at those questions, and the decision makers seemed not to experience difficulty in understanding and using the results. In those cases, the treatment of uncertainty in the models did not seem to pose a special obstacle to decision makers who would use the results. However, none of the models generated outputs that differed significantly with their sponsoring organization's policies (Bella 1987; Bella 1997).

Decision analysis often leads to a conclusion that when relevant uncertainties are large, committing to long-term courses of action is imprudent unless these actions have the built-in flexibility to respond to new information and can be reversed when circumstances dictate. Decision options to be weighed include (1) whether to continue investing in routine monitoring vs. (2) whether more information can be gained through experimental manipulation. The relative merits of the two options should be judged in terms of the value of the information they provide, expressed in terms of the desired objective (such as more fish available for harvest, or an increased probability of population persistence). The value of new information is quantified in terms of its potential to influence the selection of subsequent courses of action. Formalization of flexible decision rules together with cost–benefit analyses of continued data and experimental manipulation are included in the technical theory of adaptive management (Walters and Holling 1990).

Among the Columbia River Basin salmon modeling efforts, the PATH-EM effort represented the most substantive attempt to date to provide an analysis of the prospects for actual adaptive management (Peters and Marmorek 2001; Peters et al. 2001; Chapter 9, this volume). The analysis described specific experiments and furnished a preliminary assessment of the types of information that the experiments would provide and how much time they would require for completion. Because there seems to be a temptation, in many quarters, to co-opt the term "adaptive management" merely to put a positive spin on vague management plans, it is important that technical analyses of adaptive management continue as an ongoing enterprise connected to actual decision making.

Communication and Credibility

The best resolution of scientific disagreement among modelers is through publication in the open scientific literature, and open access to model code and data files to allow independent verification. Data access should include access to the original primary data and metadata. If there is not access to the primary data, derived quantities, when treated as if they were data, may carry errors that escape scrutiny. Because publication imposes time delays that may be inconsistent with decision time tables, it is advantageous for modeling projects to have good lines of communication with decision makers. If a modeling effort is motivated by a desire to contribute to a particular decision, it is especially helpful to ensure that the model really is addressing the right question.

Although there are exceptions, the present culture of salmon recovery in the Columbia River Basin has not put a great premium on publication, thus magnifying the importance of the decision makers' *a priori* trust in any particular modeling effort. This is not entirely a desirable situation. A greater role of publication in the open literature in establishing credibility for using science in decision making would be useful. Greater reliance on the mechanisms of normal scientific discourse might also reduce some of the contentiousness that has characterized the history of scientific debate over key issues in Columbia River Basin salmon management (Lichatowich 1999). Attempts to achieve broad scientific consensus on salmon restoration issues in the basin have not proved especially encouraging. Reaching broad consensus tends to be very slow and cumbersome—so much so that it is probably quicker to publish in the peer-reviewed scientific literature. Realistically, it is inevitable that institutional trust will give certain models and modelers an inside track for access to decision makers, but a valuing of publication and respect for published results could still influence standards of quality control and the habits of discourse for resolving scientific disagreement.

Improving Decision Support

There are two important ways in which scientists can help environmental decision processes to better cope with uncertainty. The first is the purely technical contribution of explicitly quantifying relevant uncertainties. Statements of the respective probabilities of alternative scenarios are a natural way to communicate uncertainty when the decision is essentially placing a bet about which restoration scenario actually will materialize. The second is in helping the policy makers craft decision rules that are formalized before the modeling effort is undertaken. Decision rules define the measurements that will be made, the statistical operations that will be performed on the data, and the threshold magnitudes of estimated quantities at specified levels of certainty that will serve as criteria for the decision. Such specifications help remove ambiguity from the way science is used in restoration planning, even when uncertainty exists in the data or models. Committing to these specifications in advance helps dispel suspicions that the analysis may be manipulated to achieve a particular outcome.

All the models we examined were severely constrained by lack of data. Modeling controversies in the salmon arena have sometimes been an unproductive distraction from the real scientific problem of inadequacy of information needed to address many important management questions. Some of the debate that centers on competing models could be resolved with the right data. The paucity of data creates more room for different assumptions in the models, and thus more possible outcomes. Sophisticated, responsible modeling takes plausible alternative assumptions into account, weighting them according to their respective concordance when data are available.

The aforementioned constraints need not lead to modeling wars. Areas of disagreement among models may pinpoint uncertainties that require further investigation. In considering how results of models make their way into the decision-making process, it is helpful to recall the roles of models. They provide ways of organizing and communicating information, generating hypotheses, and identifying crucial gaps in information. Modeling efforts are not ends in themselves; they are not final, definitive answers; rather, they are ongoing processes for continuously increasing knowledge.

Future Modeling in the Columbia River Basin

At this point we believe there are few compelling reasons to engage in very large, collaborative modeling efforts; in any case, large collaborative efforts in the Columbia River Basin have yielded contentious and expensive results. For the amount of real data available, the kinds of models that are actually justifiable are not that complicated. Small groups of researchers should be adequate to pursue model development, and the coherence of a small group's vision may encourage clarity. That coherence is very difficult to achieve as groups become large. In the Columbia River Basin (and perhaps in other large-scale restoration efforts), the past hope for developing region-wide collaborative modeling efforts was to achieve scientific consensus. In fact, we found that scientific consensus did not really emerge from regional modeling committees. Scientific consensus requires a much larger scientific audience, whose primary route of exposure to information is through publications, mostly in peer-reviewed books and journals. Scientists also need to resolve major differences by duplicating either analyses of the same data or experiments in the same system.

Funding specific groups to undertake specific modeling projects may be a more efficient and, ultimately, more effective approach in many river restoration arenas. We encourage delivery of model-based reports in a form suitable for peer-reviewed publication. The length limitations of publication may preclude some important detail, so it is to be expected that there will be "long-form" reports as well (which may include data archives) that should be in electronic form accessible on the internet. The expectation will be that reports delivered in a form suitable for peer-reviewed publication actually will be submitted for publication. However, we recognize that the review (and possible revision) and publication process usually involves a lag time of up to 2 years. Long lag times should not be used as an excuse not to pursue publication. It is true that managers often believe that they need results immediately, but it is also true that the same questions reoccur, often without satisfactory resolution. There would be merit to funding several groups to pursue modeling questions using the same data and different technical perspectives. Such efforts could encourage the evolution of new scientific insights.

Acknowledgments

We express our thanks to the Northwest Power Planning Council and National Marine Fisheries Service for financial support, and to the following scientists who provided information about their models: Bruce Rieman, Philip Howell, and James Peterson (ICBEMP-BBN), Peter Kareiva

and Chris Jordan (CRI), Paul Wilson (PATH-FLUSH), James Anderson (PATH-CRiSP), Charlie Paulsen and Rich Hinrichsen (PATH-EM), Lars Mobrand (EDT), and Jeff Fryer and Phil Roger (CRITFC-COHORT).

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