Special Section:
Adaptive Management for Threatened and Endangered Species

Issues and Perspectives

An Introduction to Adaptive Management for Threatened and Endangered Species

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Abstract

Management of threatened and endangered species would seem to be a perfect context for adaptive management. Many of the decisions are recurrent and plagued by uncertainty, exactly the conditions that warrant an adaptive approach. But although the potential of adaptive management in these settings has been extolled, there are limited applications in practice. The impediments to practical implementation are manifold and include semantic confusion, institutional inertia, misperceptions about the suitability and utility, and a lack of guiding examples. In this special section of the *Journal of Fish and Wildlife Management*, we hope to reinvigorate the appropriate application of adaptive management for threatened and endangered species by framing such management in a decision-analytical context, clarifying misperceptions, classifying the types of decisions that might be amenable to an adaptive approach, and providing three fully developed case studies. In this overview paper, I define terms, review the past application of adaptive management, challenge perceived hurdles, and set the stage for the case studies which follow.

Keywords: adaptive management; decision analysis; endangered species; structured decision making; value of information

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Introduction

Management of threatened and endangered species requires decision making in the face of uncertainty. This gives rise to two needs: understanding the decision context of threatened species management, and understanding how to make decisions when we do not know everything we would like to know. These are the realms of structured decision making and adaptive management, respectively, two overlapping sets of tools from the field of decision analysis that can help managers understand, frame, analyze, communicate, and implement their decisions. There is widespread use of decision-analytical techniques in threatened species management; indeed, one might view the field of conservation biology as having provided a quantitative framework for analysis of decisions about vulnerable species, and this has continued, with recent emphasis on formal application of decision theory for conservation management (Gregory and Long 2009; Converse et al. 2011; Runge et al. 2011*a*). Adaptive management—structured decision making for recurrent decisions in which uncertainty is an impediment—has enjoyed popularity in the literature since its first suggestion (Walters 1986) and has found application in many management contexts, but has not been as readily applied to threatened species management. Why might this be? On the face of it, adaptive management seems the perfect tool: it promises methods for decision making in the face of uncertainty, with the ability to respond as information is acquired. Threatened species management is deeply challenged by uncertainty, so why isn't

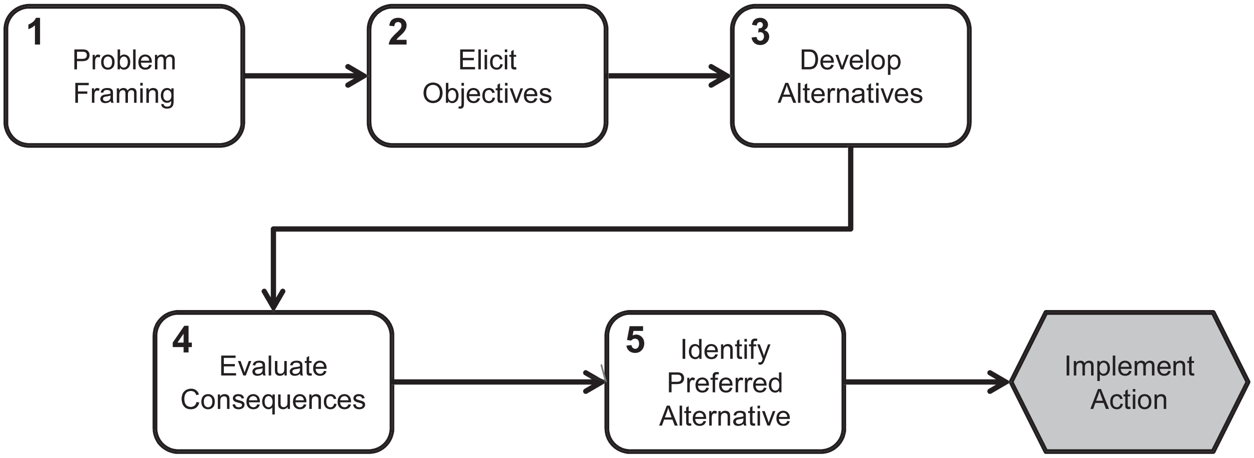

Figure 1. A schematic for structured decision making. A values-focused thinking approach to decision analysis places emphasis on identification of objectives, and uses those to motivate subsequent evaluation. The crux of the analysis is finding a preferred alternative that best achieves the objectives.

this a perfect match? It has become popular to write about the challenges and failures in implementation of adaptive management (McLain and Lee 1996; Gregory et al. 2006; Allen and Gunderson 2011) and many of the impediments to its application also apply in the context of threatened and endangered species management. But there may also be misperceptions and psychological hurdles that are unique to threatened species management.

The purpose of this special section of the *Journal of Fish and Wildlife Management* (*JFWM*) is to reinvigorate the implementation of adaptive management, where appropriate, for decisions about threatened and endangered species, by clarifying concepts, challenging misperceptions, reframing the decision context, and providing several applied case studies. The focus in this paper and the companion papers (Johnson et al. 2011; Moore et al. 2011; Tyre et al. 2011) is on application of adaptive management in the context of the U.S. Endangered Species Act (ESA) as amended (ESA 1973), both because that is where our experience lies and because one of the primary audiences of this journal has responsibility for management under the ESA. We believe, however, that the insights of this special section apply more broadly to management of threatened species by state, federal, and private agencies throughout the world, and we have endeavored to make our contributions accessible to this larger audience. In this paper, I provide definitions of terms, discuss the impediments to implementation of adaptive management for threatened species, outline how adaptive management can be applied to the variety of decision contexts related to threatened species, and briefly review the three case studies that follow in the subsequent papers.

Structured Decision Making

In the past two decades, ''structured decision making'' has come to refer to the application of formal decision-analysis tools to natural resource management decisions (Bain 1987; Ralls and Starfield 1995; Gregory and Keeney 2002). The set of decision-analytical tools is large and varied, so the applications that fall under the name ''structured decision making'' include a wide range of methods, among them the use of multiattribute utility theory (Bain 1987), info-gap decision theory (Regan et al. 2005), expected value of information (Runge et al. 2011*b*), expert elicitation (Kuhnert et al. 2010), stakeholder engagement (Irwin and Freeman 2002), and methods for integrating scientific and traditional knowledge (Failing et al. 2007). There is, however, a common framework that underlies all of these applications, namely, a fixed view of how decisions are constructed, grounded in value-focused thinking (Keeney 1996).

The core steps in a decision analysis are 1) understanding the context in which the decision is made, 2) eliciting the fundamental objectives, 3) developing a set of alternative actions, 4) evaluating the consequences of the actions relative to the objectives, and 5) identifying a preferred action that is expected to best achieve the objectives (Figure 1; Hammond et al. 1999). This deconstruction allows the analyst to help the decision maker identify the primary impediments to a decision and select tools to overcome those impediments. One of the most important hallmarks of structured decision making is the emphasis on value-focused thinking, which places a primacy on early identification of the decision maker's objectives; these objectives drive the remainder of the analysis (Keeney 1996).

This framework is as valuable for analyzing decisions about threatened and endangered species as it is for other applications in natural resource management. At the problem-framing stage (step 1, Figure 1), the challenge is to understand the nature of the decision being made, and the biological, legal, and social context in which it occurs. Is this a decision about whether and how to list a species under the ESA or some other law? Is it a decision about what management actions to take to best achieve recovery? Is it a decision about whether to permit a proposed project that might result in incidental take (i.e., lethal or non-lethal harm that accompanies an otherwise lawful activity)? In many countries, decisions regarding endangered species are regulated under special statutes, like the ESA in the United States, the Species at Risk Act in Canada (SARA 2002), the Environmental Protection and Biodiversity Conservation Act in Australia (EPBC 1999), the Bern Convention on the conservation of European wildlife and natural habitats in the European Union (Bern Convention 1979), and the Convention on International Trade in Endangered Species (CITES 1973) worldwide. The particular details of these statutes and conventions, and the regulations that derive from them, are important in understanding the nature of any decisions about protected species. Just as important is to understand the current biological context; for example, what is the current status of the species, what are the factors that threaten its persistence, and how much take is already occurring? Finally, what is the social context in which the decision is being made? Are there competing interests and multiple stakeholders? Are there potential management partners? By understanding the context in which a decision is being made, the decision makers and analysts can better begin to frame the decision and select the tools that will be valuable in its analysis.

Problem framing paves the way for discussion of objectives (step 2, Figure 1), the outcomes the decision maker aspires to achieve through the decision. Of particular importance is a focus on fundamental objectives (the core outcomes sought as a result of the decision), as contrasted with means objectives (objectives sought not for their own sake, but only as a means to achieve fundamental objectives). One of the biggest challenges in natural resource management is that there are often many competing fundamental objectives, and any choice of action entails trade-offs among these objectives. The first step to navigating these trade-offs is a full articulation of the multiple objectives of concern. In decisions about threatened and endangered species, there is often a legislated objective to maximize the likelihood of persistence of the species in question. But there may be many other objectives at play; for instance, minimizing the time to recovery, minimizing the costs of recovery, minimizing regulatory burden on the public, protecting economic activity, and providing recreational opportunities. The regulatory context may provide guidance on which objectives are germane or have prevalence, but understanding the full suite of objectives for the decision makers and stakeholders is important, particularly because it may lead to decisions that are robust and enduring. A second component of articulating objectives is developing measures by which they can be gauged (Keeney and Gregory 2005), thus, allowing quantitative analysis. Developing these measures is often very difficult, in part because it requires clarifying the precise aspirations embodied in an objective, including the spatial and temporal aspects. For endangered species, there is a large literature on the probability of extinction as an appropriate measurable attribute for the objective of minimizing extinction (a couple of key entry points to this literature include Shaffer [1981], Ralls et al. [2002]), but there is a growing realization of how difficult it is to capture our societal expectations in this regard (DeMaster et al. 2004; Regan et al. 2009).

A decision is, of course, the selection of a preferred action from a set of potential alternative actions. Developing the set of alternative actions (step 3, Figure 1) ideally proceeds after objectives have been articulated, so knowledge of the desired long-range outcomes can help guide the crafting of alternative strategies. In some decisions, the set of alternatives can consist of just a few discrete options (e.g., classifying a species as ''endangered,'' ''threatened,'' or not warranted for placement on a list of vulnerable species), but in others the set of alternatives may be a complex mix of discrete and continuous options (e.g., all the combinations of actions that might contribute toward species recovery). The task of developing alternatives has both science- and values-based facets. Part of the problem is technical (what options are even known that might contribute toward achievement of the objectives?), but part of the problem is values-based (what options are palatable enough to be included, and does the set of alternatives represent solutions proposed by a range of stakeholders?). Development of alternatives can be a valuable way to engage stakeholders and scientists in a collaborative effort that creates the necessary tools for further steps of analysis, while also possibly shedding greater light on the objectives that are important (as an example, see Runge et al. 2011*a*). Structured decision processes often carefully separate development of alternatives from evaluation of them, to build a rich set of options through creative exploration and out-of-the-box thinking.

At the core of any decision is a set of predictions about how well the alternatives under consideration will perform with regard to the objectives. The evaluation of these consequences (step 4, Figure 1), which should follow articulation of the objectives and development of the alternatives, often involves the use of predictive models. In a structured decision making approach, the model requirements are provided by the needs of the decision (Starfield 1997), which can be a startling departure from common practice for scientists who are accustomed to making predictions in the absence of discussion with decision makers. For threatened and endangered species management, there is a long history of predictive modeling; the phrase ''population viability analysis'' now refers to the array of tools available for predicting probability of persistence (Beissinger and McCullough 2002). But predictive models are needed for all of the objectives under consideration. For instance, a full decision analysis of alternatives for recovery of an endangered species might need to make predictions not only about the persistence of the species but also the economic impacts, the opportunities for recreation, and the regulatory burden placed on private landowners. Predictive models can take a number of forms, including quantitative models based on empirical evidence, conceptual or quantitative models derived from formal expert elicitation, and models based on traditional ecological knowledge. All of these types of model, however, perform the same function: they predict the outcomes associated with the alternative actions in terms that are relevant to the decision maker's objectives.

With objectives, alternatives, and predictions of consequences in hand, the decision maker has a lot of information to inform the decision, but the task is not yet complete. The key step is to identify a preferred alternative among the set being considered (step 5, Figure 1), an alternative that best achieves the objectives. In simple cases, the preferred alternative is evident as soon as the consequences are predicted, but in many cases, this is not a trivial step. First, if the alternatives being considered are complex, numerous portfolios of component actions, advanced optimization techniques may be required to search among the large set of alternatives for the one that performs best. Second, it may be difficult to measure ''best'' in that it requires balancing trade-offs among multiple objectives. In the latter case, the use of multicriteria decision analysis is beneficial (Keeney and Raiffa 1976; Herath and Prato 2006).

This five-step approach to decision analysis (problem, objectives, alternatives, consequences, and trade-offs; Hammond et al. 1999) provides a valuable framework to structure a decision process (Figure 1). In many decisions, other analytical tools are also needed, such as ways to handle risk, to cope with uncertainty, or to assess the value of information. Facilitation tools are also often needed, such as ways to engage stakeholders, build consensus, elicit expert judgments, or document and communicate the outcomes of the decision process. There is increasing recognition that robust and enduring decisions regarding threatened and endangered species need to make use of the large set of tools available from the field of decision analysis.

Adaptive Management

Structured decision making refers to the use of decision-analytical tools to aid natural resource management and, thus, is an umbrella concept that covers a broad set of decision problems. Adaptive management is a special case of structured decision making for recurrent decisions made under uncertainty. Many natural resource management settings, including many threatened and endangered species management decisions, have two key features: they are recurrent, in that the decision is revisited repeatedly; and they are plagued by uncertainty, in that the consequences of the alternatives are not known with certainty. The first feature gives rise to the need to understand the dynamic nature of the decision—actions taken now affect decisions that can be made in the future, as well as the outcomes of those future actions. These dynamics can be complex, and can make it challenging to identify an optimal strategy. Fortunately, there are analytical techniques designed for such dynamic decisions. The second feature gives rise to the need to know how to make decisions in the face of uncertainty—what are the possible uncertain outcomes and how does the decision maker feel about the risk imposed by that uncertainty? Again, there are decision-analytical tools designed to manage in the face of uncertainty. When these two features occur together (dynamic decisions in the face of uncertainty), there is an added complexity—is there value in reducing uncertainty so that future decisions can be more informed, and can actions taken now help to reduce that uncertainty? The ability to adapt future decisions to new information is the hallmark of adaptive management.

The first impediment to the application of adaptive management may well be that no one knows what it means, or rather that people mean so many things when they use the term that it has ceased to be useful. McFadden et al. (2011) provide the beginnings of a long-needed taxonomy, identifying two primary schools of thought surrounding adaptive management: the Resilience–Experimentalist (RE) school, exemplified by Gunderson et al. (1995); and the Decision–Theoretic (DT) school, exemplified by Williams et al. (2007). The RE school has arisen from efforts to manage large-scale, complex socio-ecological systems, like the Columbia River (Lee and Lawrence 1985), the Everglades (Walters et al. 1992; Gunderson and Light 2006), and the Grand Canyon (Meretsky et al. 2000; Hughes et al. 2007; Coggins 2008). In these examples, the social and political dimensions are multifaceted and complicated, and the ecological dimensions are dynamic, complex, and poorly understood, so it stands to reason that the emphasis is on collaborative and adaptive governance, institutional and ecological resilience, and reduction of uncertainty through experimental manipulations. The DT school emphasizes formal tools of decision analysis, with incorporation of predictive modeling and optimization that anticipates the value of learning. Grounded in the seminal works of Holling (1978) and Walters (1986), the DT school was perhaps most profoundly influenced by the adaptive harvest management of waterfowl in the United States (Johnson et al. 1997; Nichols et al. 2007). In this example, a single agency, the U.S. Fish and Wildlife Service (Service), has regulatory authority for the decision, a decision which is revisited annually. Here, the emphasis is on managing a dynamic system in the face of uncertainty, with reduction of uncertainty not occurring experimentally, but rather through the ongoing management and monitoring of the system. The approach taken by the DT school is applicable to a wide variety of settings, from narrow to broad scope, where recurrent decisions are impeded by uncertainty (Williams et al. 2007).

In this special section of *JFWM*, we are emphasizing the application of tools from the DT school of adaptive management to decisions involving threatened and endangered species. To the five core steps of decision analysis (as outlined above in ''Structured decision making''), the DT school adds an additional four: 6) articulating critical uncertainty, 7) designing and implementing an appropriate monitoring system, 8) updating the predictive models based on ongoing monitoring information, and 9) adapting future decisions based on the new understanding of how the system responds to management (Figure 2).

The central motivation of adaptive management is that there is critical uncertainty about how the ecological system in question responds to management, and this uncertainty impedes decision making. A formal adaptive management framework, then, includes the articulation of that key uncertainty (step 6, Figure 2). To the DT school, this means explicit description of alternative

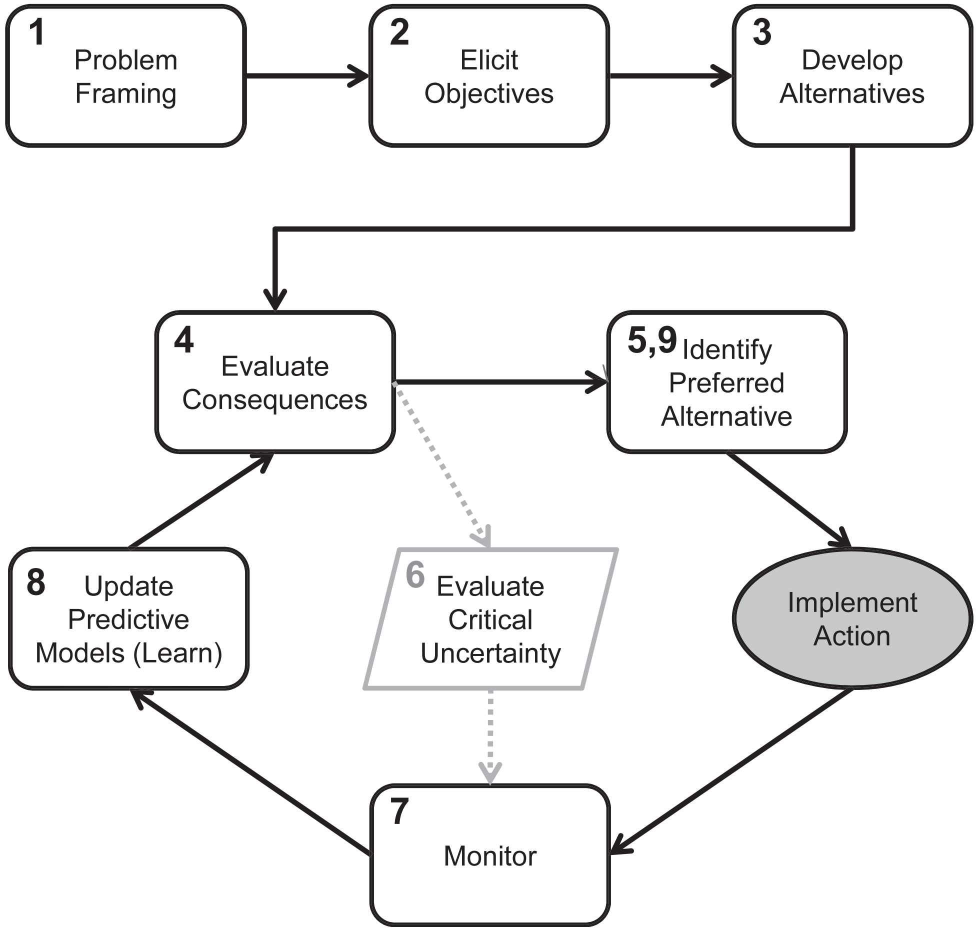

Figure 2. A schematic for adaptive management. At the core of adaptive management is critical uncertainty that impedes the identification of a preferred alternative. When decisions are recurrent, implementation coupled with monitoring can resolve uncertainty, and allow future decisions to reflect that learning.

hypotheses, in the form of multiple predictive models. For these alternative models to represent critical uncertainty, they must lead to different recommended actions; in the language of decision analysis, there is a high value of information in resolving the uncertainty (Runge et al. 2011*b*). In this spirit, adaptive management is not an unfocused admission that future management will change as a result of information that accrues, whatever that information may be, but rather, adaptive management includes a specific articulation of what information is being sought and precisely how it will change future decisions. As an example in the management of endangered species, Moore et al. (2010) describe uncertainty in the demographic rates of released whooping cranes *Grus americana*, the resolution of which would strongly influence whether or not continued releases of captive-bred individuals would contribute to recovery of the Florida nonmigratory population.

In the context of adaptive management, one of the primary purposes of monitoring is to reduce the critical uncertainty that impedes management (Nichols and Williams 2006; Lyons et al. 2008); thus, monitoring design (step 7, Figure 2) follows directly from articulation of critical uncertainty. In this sense, monitoring is "targeted" specifically at those hypotheses that represent uncertainty (Nichols and Williams 2006). This approach makes efficient use of scarce resources, allocating funds and staff time only to monitoring that is expected to improve long-term management.

Each of the alternative models makes a prediction about what will happen after implementation of a particular management action, and the monitoring program gathers data about the observed response. The comparison of the observed response to the predicted responses allows the predictive models to be updated (step 8, Figure 2). Often this updating is done using Bayes' Theorem to increase the belief in models that match more closely the observed response, and decrease belief in models that did not perform as well. As information accrues over time with multiple management decisions, the key uncertainty should be reduced.

The reduction of uncertainty itself, however, is not the goal, or even the hallmark, of adaptive management. Rather, the adaptation occurs when the new knowledge of the system is used in making subsequent decisions (step 9, Figure 2). As critical uncertainty is reduced, the predictive models should point more assuredly toward one strategy or another.

In its most complete quantitative form, adaptive management is an exercise in adaptive dynamic optimization—

the search for an optimal strategy that anticipates the long-term implications of any one action, and also anticipates how learning will accrue and influence future decisions. There are mathematical algorithms (active adaptive stochastic dynamic programming) for solving such problems, if they can be fully articulated (Williams 1996). These approaches are promising for management of threatened and endangered species, because they seek to make decisions that account for the risks inherent in stochastic processes as well as the opportunities that exist if learning can be harnessed.

Applications of Adaptive Management for Threatened and Endangered Species Management

The literature on applying adaptive management to threatened and endangered species management falls into three categories: articles that extol the potential, articles that describe the challenges and impediments to implementation, and articles that document actual application.

Many authors have advocated the application of adaptive management, both broadly in natural resource management, and to threatened species specifically. It is clear that the earliest articulations of adaptive management envisioned applications that could include management of threatened and endangered species (Walters 1986). A long list of authors have argued that adaptive management is a critical method for natural resource management (e.g., Humphrey and Stith 1990; Lancia et al. 1996) and Callicott et al. (1999) included adaptive management as one of the normative concepts in conservation. Specifically with regard to threatened and endangered species, Possingham et al. (1993) called for the application of adaptive management, the National Research Council (1995) noted the importance of reducing uncertainty and applying new knowledge to subsequent decisions, and Ludwig and Walters (2002) sketched a framework for integrating population viability analysis into an adaptive framework. One of the clearest theoretical demonstrations of how the DT approach to adaptive management could be implemented for endangered species was given by Goodman (2002).

More recent calls for the application of adaptive management take a more balanced tone, acknowledging the accrued experiences in implementation (Allen et al. 2011). Indeed, the most visible part of the adaptive management literature is more a catalog of failures—or at least, disappointments and impediments—than successes (McLain and Lee 1996; Lee 1999; Allan and Curtis 2005; Gregory et al. 2006).

The crux, of course, is in the application. Is adaptive management being successfully applied, particularly to threatened and endangered species? Management of salmon *Oncorhynchus* spp. in the U.S. Pacific Northwest was one of the early and iconic applications of RE-school adaptive management (Lee 1993; Smith et al. 1998). Concerns about the Kanab ambersnail *Oxyloma haydeni kanabensis*, an ESA endangered species in the Colorado River, have led to a series of adaptive management experiments, as well as the formation of the Glen Canyon Dam Adaptive Management Working Group (Meretsky et al. 2000). Bearlin et al. (2002) explored the potential for adaptive management in recovering trout cod *Maccullochella macquariensis* in the Murray–Darling Basin in Australia. Moore and Conroy (2006) developed an adaptive forest management strategy to support recovery of ESA endangered red-cockaded woodpeckers *Picoides borealis*. The investigation of experimental strategies in an adaptive framework for the endangered New Zealand hihi *Notiomystis cincta* led to successful reintroductions (Armstrong et al. 2007). Also in New Zealand, Conroy et al. (2008) developed a DT-school framework for adaptive management of the endangered Hector's dolphin *Cephalorhynchus hectori*. Adaptive management, in the spirit of the RE-school, is a central component of the management of the central Platte River in the United States, with attention to recovery of three ESA endangered species and one ESA threatened species (Smith 2011). The Service's field office in Lacey, Washington uses a decision-analytical framework to manage allocation of workload to Section 7 of the ESA, which requires consultation with the Service, and with the implementation of an appropriate monitoring program, this framework could be made adaptive (Converse et al. 2011). Although this list of applications is not complete, it does lead to several important observations. First, a review of the literature found that there is only a small number of applications of adaptive management for threatened and endangered species. Second, the literature on application is split about evenly between proposals for, and actual implementation of, adaptive management. Third, there are both RE-school and DT-school approaches being taken.

The literature on adaptive management, however, may not be representative of the practice. How many applications are implemented, but not documented in peer-reviewed journals? Many agencies across the United States and the world have guidance that indicates adaptive management is a core tenet (Linkov et al. 2006). Ruhl (2008) notes that adaptive management is firmly entrenched in U.S. natural resource management agency practice at all levels, even though it has little statutory, regulatory, or judicial mandate. Perhaps the answer to this paradox is that the routine application of adaptive management is of an informal nature that does not fully conform with formal definitions of either the RE or the DT school. Indeed, there is a wide acknowledgment that one of the impediments to application of adaptive management is the confusion over what, in fact, the term means (Allen et al. 2011). A common interpretation of adaptive management is simply an acknowledgement that management might need to change in the future because of unforeseen insights that could arise. Both the RE and DT schools reject trial-and-error as a version of adaptive management, because a trial-and-error approach cannot proactively identify what to monitor, nor how future actions might adapt as a result of learning. So perhaps the scant literature on actual application is a fair indication of the degree of implementation of formal adaptive management approaches, and the perception of widespread practice of adaptive management reflects a more informal interpretation of the concept. The question then arises, if adaptive management is a normative concept in natural resource conservation (Callicott et al. 1999), why are there not more formal applications for threatened and endangered species?

Overcoming Misconceptions

There may be a number of psychological impediments to the application of adaptive management for threatened and endangered species, above and beyond the various institutional and technical challenges that have been noted elsewhere (McLain and Lee 1996; Allan and Curtis 2005; Gregory et al. 2006). These psychological hurdles are largely misconceptions about what adaptive management is, and what is required to apply it. Recognition of these misconceptions may open the way for greater application of adaptive management.

Misconception 1: adaptive management is for large-scale projects

The most visible and celebrated applications of adaptive management are for very large systems like the Everglades, the Great Barrier Reef, the Grand Canyon, the Columbia River Basin, and North American waterfowl (Lee and Lawrence 1985; Gunderson and Light 2006; Hughes et al. 2007; Nichols et al. 2007). This leads to the impression that adaptive management is only for large-scale projects, which may deter decision makers from considering its application at other scales. But the issue of having to make decisions in the face of uncertainty is not scale-dependent. Uncertainty and the opportunity for its reduction through learning are present at local scales, as well as watershed, basin, and national scales. Two components of adaptive management, stakeholder involvement and complex ecosystem dynamics, appear to suggest larger scale projects are more appropriate. Stakeholder involvement, which is emphasized by both the DT and RE schools, may be more complicated for large-scale projects, but there can be complex and contentious stakeholder concerns at even the smallest scale of project. Further, both schools simply emphasize the need to involve all relevant stakeholders; if there is only one stakeholder (the sole decision maker), adaptive management may still be appropriate. Complex ecosystem dynamics, and the inherent uncertainty associated with them, are one of the motivations for adaptive management for the RE school and may suggest the suitability of adaptive management for large-scale problems in which the dynamics are quite complex. Again, the issue here is not the scale of the problem, but uncertainty acting as an impediment to the decision.

Small-scale decisions, if they are impeded by uncertainty and if there is the opportunity to apply learning to subsequent decisions, can benefit just as much from adaptive management as large-scale decisions. In fact, it might be easier to apply adaptive management to smaller scale problems, where there are fewer complications to contend with. Further, expanding the practice of adaptive management through greater application at a variety of scales may allow us to move more effectively from theory to implementation (McFadden et al. 2011).

Misconception 2: adaptive management requires a big investment

A similar psychological impediment arises from the visibility of large-scale projects—the impression that adaptive management requires a large investment of time and money to initiate and maintain. The Glen Canyon Dam adaptive management program has been engaged in active planning since its establishment in 1997 and will be supported by nearly \$11.5 million in fiscal year 2012 (Adaptive Management Work Group minutes, attachment 7a, May 18, 2011). The Comprehensive Everglades Restoration Plan is expected to require over \$10 billion of investment over 30 y. The harvest management of North American waterfowl was built on a 4-decade database, although the development of the adaptive framework occurred quite quickly (Johnson et al. 1997). Do all adaptive management projects require years to develop, millions of dollars to maintain, and decades to implement? In short, no. Adaptive management is, and should be, scalable to the problem at hand. The degree of investment for development and maintenance should be commensurate with the scale and importance of the problem. Yes, large-scale problems with large sets of stakeholders will require an extensive investment in planning. But smaller scale frameworks can be developed more quickly. The framework for adaptive management of Hector's dolphins was developed during a 3-d workshop (Conroy et al. 2008). Yes, all adaptive management projects require an investment in ongoing monitoring to provide the feedback and learning that allow management to improve over time, and this investment can be an impediment. But the investment in monitoring should be focused on the critical uncertainty for the decision in question and, thus, scaled to the particular problem (Lyons et al. 2008; Runge et al. 2011*b*). Adaptive management only requires targeted monitoring needed to support the decision, not broad-based surveillance monitoring (Nichols and Williams 2006); further, adaptive management is only warranted if the expected value of learning exceeds the costs of monitoring.

Misconception 3: the risks are too high for endangered species

An impediment to implementation of adaptive management specifically for threatened and endangered species is the perception that the risks of such implementation are too high. Blumstein (2007:552) asserts that he knows "of few managers working with critically endangered species who are willing to employ active adaptive-management experiments." Ludwig and Walters (2002:511) note that "…the large risks associated with experimental policies may often preclude their adoption." Allen and Gunderson (2011), speaking specifically about critically endangered species, argue that adaptive management may not be appropriate when the risks of the outcomes are too great. Volkman and McConnaha (1993:1261) note that one of the challenges to implementation of adaptive management for salmon in the Columbia River was the difficulty of convincing people of the wisdom of ''risking harm to a species on the brink of extinction.''

This misconception may arise from thinking that adaptive management requires designed experiments that cannot take into account the risk tolerance of the decision maker. This may be a failing of the RE school, in fact, in emphasizing experiments as the basis for learning. The DT school of adaptive management, however, readily handles this concern. When learning is seen as an integrated component of management, and when learning is pursued only insofar as it increases the long-term expected performance of management, the risks of learning are folded into the pursuit of adaptive management. Thus, if a particular action is expected to generate valuable insight that could greatly improve future management, but if it also carries a high probability of extirpating the population, that action would not be recommended, because long-term achievement of management goals is only possible if the population remains extant. In other words, as long as the short-term risks of learning are explicitly embedded in the decision analysis, an adaptive approach will be compatible with endangered species management, and indeed, will identify the smartest course of action that accounts for management objectives in the face of uncertainty. Note that the smartest course of action, in an adaptive framework, may be *not* to pursue learning, if the risks associated with that learning are too high. But that conclusion can only be reached from full decision analysis of the problem in a context that considers the appropriate value of learning in an adaptive setting.

Several of the authors that have mentioned this concern know that it is a misconception. The Department of Interior Technical Guide for adaptive management identifies a limitation of adaptive management when ''risks associated with learning-based decision making are too high'' but goes on to say that an adaptive management approach can alleviate those risks through careful articulation of objectives, actions, and models (Williams et al. 2007:16), in other words, through a full decision-analytic approach. Allen and Gunderson (2011), after raising concerns about application of adaptive management when the risks of failure are too high, go on to suggest that a structured decision making approach may be warranted, which simply means that the full nature of the decision problem needs to be articulated.

Misconception 4: the law does not allow adaptive management

Another impediment to implementation of adaptive management for threatened and endangered species is the perception that the law does not allow such application. This concern is usually raised with regard to procedural laws, but it can also be a concern under regulatory laws. In the United States, regulatory decision making for threatened and endangered species is governed by the ESA, but also by the National Environmental Policy Act (NEPA, 42 USC 4321 et seq.) and the Administrative Procedure Act (APA, 5 USC 500 et seq.). The National Environmental Policy Act and the Administrative Procedure Act specify how regulatory decisions are to be made and provide for public input in the development of government actions. The general idea is that the government describes what actions it intends to take, allows public review, revises the proposal as appropriate based on public comments, then implements it. The suggestion has been made that adaptive management may not be possible under current administrative law in the United States (Ruhl 2005, 2008) in part because experimentation is limited by the certainty required by law (Doremus 2001; Garmestani et al. 2008). Under this view, adaptive management does not provide the public with sufficient certainty about what the government is going to do, allowing the government to change its actions as more information becomes available.

This concern, it appears to me, arises from an informal trial-and-error interpretation of adaptive management. If, instead, we mean by adaptive management the prior articulation of uncertainty and an advanced specification of what different actions will be taken under different monitoring outcomes, then we can provide considerably more guidance to the public about what the actions and their consequences may be. The Department of Interior technical guide (Williams et al. 2007:40) elaborates on this with regard to the National Environmental Policy Act,

> An [Environmental Impact Statement] incorporating adaptive management…needs to clearly describe how the approach would be implemented. This not only includes what types of actions are proposed initially, but also the results that are expected from monitoring and assessment, and future actions that may be implemented based on those results. Decision makers and the public must be able to see how the adaptive management approach would be implemented, including potential future actions and anticipated impacts on the environment.

Williams et al. (2007) also note that if monitoring reveals new, significant information that was not anticipated at the time of the original planning document, then a supplemental planning process should be initiated (e.g., a Supplemental Environmental Impact Statement under the National Environmental Policy Act).

The concern raised by this misconception is not unique to the United States. Other legal systems have to grapple with the same tension between the rights of citizens for some certainty about the regulatory burden the government may place on them and the need for flexibility on the part of the government to carry out mandates for the good of the country. A transparent, adaptive approach can be used to share fairly the burden of uncertainty among affected parties.

Potential Applications Under the ESA

As noted above, and discussed by many other authors, the potential for application of adaptive management to threatened and endangered species is considerable. Many of the decisions are revisited in some way over time and are impeded by uncertainty. Indeed, because of these uncertainties, as well as the complexities and variation in the ecosystems in which imperiled species are found, Ruhl (2004:1263) argues that adaptive management is ''the only practical way to implement the ESA.'' But what are the specific opportunities for application of adaptive management under the ESA and other similar laws across the globe? What decisions are made, and when might adaptive management be appropriate and advantageous?

Recovery actions

Perhaps the most obvious application of adaptive management for threatened and endangered species is in the implementation of recovery actions, the on-the-ground local management that, in the end, needs to be the foundation of recovery. In the United States, the ESA requires the development of a recovery plan for each listed species; this is a key provision of the law that goes beyond limiting further decline to promoting an increase in the status of the species. While the planning itself could be adaptive, the more tangible potential is in adaptive implementation of the actions called for by the plan. Foin et al. (1998) break management into three categories based on intensity: habitat preservation, where protection needs to be provided, but otherwise, the conditions exist for recovery; habitat restoration, where the quality of existing potential habitat needs to be improved to support recovery; and active management, where ongoing human intervention is needed to prevent further decline and promote recovery. Actions in all of these categories may be recurrent, and may be uncertain, so the potential for adaptive management exists.

Many recovery actions are recurrent, that is, a similar decision is made repeatedly, either at the same place or at different places over time. For example, a tract of land managed for early successional species may need to be disturbed repeatedly over time, perhaps through fire or mowing; each year, there is a recurrent decision to implement disturbance or not, and if so, by what means. The recurrence, of course, provides the opportunity to apply learning derived from previous responses to management (if appropriate monitoring is implemented). The recurrence can also be spatial. For example, consider actions that involve habitat acquisition, either through title or easement. It would seem that these are one-off decisions, nonrecurrent opportunities to either acquire a parcel or not, which provide no opportunity for learning because the decision is not revisited. But if the decision maker considers the *program* of acquisition, rather than the decisions about individual parcels, the decision about each new parcel is recurrent and possibly adaptive, because the learning that is acquired through one acquisition can be applied to decisions about subsequent acquisitions. This notion of programmatic learning is important, if underutilized, for broader application of adaptive management.

Recovery implementation is also often impeded by uncertainty. The status of the imperiled species may not be well-known, the threats may be undiscovered or disputed, and the best ways to address the threats and promote recovery may be uncertain. As an example, the Platte River Recovery Implementation Program seeks to support recovery of four species (interior least terns *Sternula antillarum athalassos*, piping plovers *Charadrius melodus*, whooping cranes, and pallid sturgeon *Scaphirhynchus albus*) by increasing appropriate habitat conditions. Two potential strategies are being explored to achieve these goals: restoration of braided channel morphology through pulse flows, sediment augmentation, and mechanical actions; and mechanical creation and maintenance of habitat, without flow manipulations or sediment augmentation. It is not clear which of these strategies will be most successful in achieving the array of recovery objectives; thus, they are being implemented adaptively (Smith 2011).

The scale of recovery actions can vary greatly, reflecting the authority of the given decision maker. On one extreme, a single landowner might be considering management actions on a small parcel; on the other extreme, a multiagency recovery team might be considering a complex array of actions over many jurisdictions within a watershed or ecoregion. Throughout that continuum, adaptive management holds promise.

Not all situations, however, call for adaptive management. First, for decisions that are truly not recurrent, no adaptation is possible. Second, if uncertainty is not an impediment, adaptive management is not necessary. Smith (2011) puts it nicely, noting that the Platte River program focuses on ''need to know'' rather than ''nice to know'' information, echoing calls elsewhere for adaptive management to be driven by the value of information (Doremus 2011; Runge et al. 2011*b*).

Incidental take authorization

Many imperiled species laws, like the ESA, prohibit lethal or nonlethal take of listed species, even if it is incidental to the action being undertaken. As an inflexible criterion that does not allow compromise, prohibition of take can be a substantial regulatory burden, so many of these same laws have provisions for authorizing incidental take in some circumstances, particularly if such authorization motivates net positive benefits for the species. Under the ESA, U.S. federal agencies have an obligation under Section 7 to consult with the Service (or National Oceanic and Atmospheric Administration-Fisheries, which has jurisdiction under the ESA for marine and anadromous species) to ensure that any actions they take or authorize are not ''likely to jeopardize the continued existence'' of the species; incidental take can be authorized provided this ''jeopardy standard'' is met. Nonfederal landowners wishing authorization for take that is incidental to an otherwise lawful activity must also meet the jeopardy standard and further must develop a conservation plan (often referred to as a Habitat Conservation Plan) that describes how such take will be minimized and mitigated.

It is difficult to predict the long-term outcomes of actions that may result in incidental take and any mitigation that goes with them; thus, uncertainty can be an impediment to authorization of incidental take (McGowan et al. 2011). In theory, adaptive management could relieve some burden by allowing actions to go forward that a strongly precautionary approach would otherwise prohibit, provided they are accompanied by appropriate monitoring and the capacity to adapt in the future as information accrues (Doremus 2001; Ruhl 2004). In practice, the application of adaptive management in these settings is challenging; first, because it is not always the case that the decisions are recurrent or reversible, and second, that there may not be the regulatory mechanisms or the willingness for agencies to make the monitoring and adaptation binding.

Under the ESA, many Section 7 consultations and Habitat Conservation Plans are in fact, or are treated as, one-off, not recurrent, decisions. The applicant (whether a public or private entity) and the Service negotiate a set of actions and mitigations that protect the species, promote recovery, and provide the achievement of the applicant's objectives; the actions are implemented; and the story ends. For some actions, like the construction of a hydroelectric dam or a real-estate development, it does certainly seem like the actions cannot be revisited or reversed, in which case, adaptive management is not an appropriate paradigm. But, two approaches open up the potential for adaptive management. First, many large projects have incremental stages that could be implemented adaptively. Indeed, the Service often consults on an on-going basis for long-term projects, and Habitat Conservation Plan guidance calls for the use of adaptive management when appropriate. When the recurrent or incremental nature of a large project allows implementation, monitoring, and feedback, adaptive management can be used to enhance long-term outcomes. Second, a *programmatic* approach to consultation or habitat conservation planning recognizes that the learning afforded by one project can be applied to subsequent projects. For example, when the Army Corps of Engineers issues a permit for construction of a private dock in coastal waters in Florida, they must consult with the Service to determine whether that dock will jeopardize the endangered Florida manatee *Trichechus manatus latirostris*. These consultations were previously conducted on a one-by-one basis, and afforded no opportunity for learning or adaptation. In 2011, the Army Corps of Engineers consulted with the Service on their *program* of dock permitting. The primary purposes of this programmatic consultation were to streamline the permitting process and account for accumulated impacts, not to address uncertainty. But such a structure could take a formal adaptive management approach to articulate how the Corps would adjust future permitting as learning accrued.

There is a substantial literature on Habitat Conservation Plans under the ESA, and the challenges and potential for incorporating adaptive management (Ruhl 1990, 2005; Doremus 2001; Wilhere 2002, 2009). In essence, there is an interesting tension between the motivations of the applicant and the Service. The applicant is concerned about regulatory certainty—knowing what they will be required and allowed to do. The Service is concerned about biological certainty—knowing that the species is not being placed in jeopardy. Adaptive management will be most advantageous when it serves both motivations by balancing and then reducing the burden of uncertainty, providing clarity and minimal regulatory constraints to the applicant while simultaneously achieving greater recovery potential for the species.

Listing and delisting

Finally, there are the classification decisions that govern when species are added to or taken from the list of threatened and endangered species. At first glance, it seems these classification decisions are not candidates for adaptive management—we hope not to be making a recurrent listing decision for the same species. But both listing and delisting can be viewed as recurrent decisions, even for a given species: the status of a candidate species is reviewed periodically (at least implicitly) until such a time that it warrants listing; likewise, the status of a listed species is reviewed periodically until such a time that it warrants delisting. (Under the ESA, the statutory requirement for a 5-y status review of each listed species essentially specifies a recurrent decision about reclassification or delisting, Ruhl 2004). Here, one of the real impediments to either decision is uncertainty about the status of the species; frequently, the population size, spatial extent, genetic composition, demographic rates, and threats are not well-known, so the classification decisions must be made in the face of uncertainty. With monitoring in place, and the status being updated in light of monitoring data, an adaptive approach to classification can be taken (Prato 2005).

A programmatic approach to listing and delisting would be amenable to adaptive management. Many classification systems for threatened and endangered species, like the ESA, International Union for Conservation of Nature Red List (IUCN 2001), and other systems, implicitly involve forecasting the probability of extinction, but often rely on more proximate measures (like population size or trend, geographic extent, etc.). Two important uncertainties arise: how good are we at predicting probability of extinction; and how good are the proxy metrics at approximating it? It would not be possible to evaluate these questions on any one species, but a programmatic assessment of our ability to make these predictions is possible (Keith et al. 2004). Undertaken adaptively, such a programmatic system would allow us to improve the methods by which we classify species as threatened or endangered.

Overview of Case Studies

In the next three papers, we illustrate the application of adaptive management to threatened or endangered species. These case studies were developed collaboratively by managers, scientists, and decision analysts in focused workshop settings that allowed the groups working on the three case studies to share insights with one another. In all cases, these are real management problems being faced by the Service as it seeks to recover these species under the ESA. In choosing these case studies, we sought decisions being made at the lowest administrative level of the Service (the field office level, roughly the size of a U.S. state), to provide manageable examples that are typical of a large number of decisions and to counter some of the stereotypes about adaptive management.

All three case studies focus on the role of uncertainty as an impediment to decision making in support of the conservation of these species, recognize the iterated nature of decisions, and then employ a formal adaptive management framework to suggest a solution. All three case studies concern recovery planning, namely, which actions are most likely to conserve the species, when and under what conditions to take those actions, and how to balance the desire for recovery with the real limitations of budgets, staff, and uncontrollable uncertainties.

The Florida scrub-jay *Aphelocoma coerulescens* is a threatened bird subspecies endemic to scrub habitat in Florida. Landscape fragmentation and fire suppression have modified many scrub communities to the point they can no longer support scrub-jay populations. At the scale of sites that are managed primarily for scrub-jays, the decision impediments have to do with knowing what habitat actions are optimal and the frequency with which they should be applied. In the first case study, Johnson et al. (2011) develop a state-dependent decision framework for management of scrub habitat at the site level in support of scrub-jay recovery. The predictive model for the system includes two components: predicting the habitat transitions as a function of the action taken; and predicting the annual growth rate of scrub-jays as a function of the habitat state. Johnson et al. (2011) derive an optimal state-dependent management strategy, but find that even under this optimal strategy, the expected long-term scrub-jay growth rate is only 0.89, suggesting that decline is unavoidable. Although uncertainty about the habitat transitions leads to different state-dependent strategies, the long-term results are largely unchanged. That scrub-jay recovery does not appear to be possible with current tools even under an optimal management strategy suggests that innovative new methods of management need to be found.

Mead's milkweed *Asclepias meadii* is a threatened perennial herb of tallgrass prairie and glade communities in the central United States. At a large scale, this plant is threatened by the destruction and alteration of its habitat through agriculture, urbanization, and recreation. At the site scale, uncertainty about how best to encourage reproduction and persistence is a primary impediment to decision making. In the second case study, Moore et al. (2011) develop an adaptive decision framework for management of this species at the site level. At the core of this framework is a predictive stage–based model for milkweed population dynamics, with characterization of the key management uncertainty. Moore et al. (2011) show that an active adaptive optimization can account for this uncertainty, and that implementation of this adaptive strategy is expected to improve long-term outcomes.

Bull trout *Salvelinus confluentus* is a threatened salmonid broadly distributed in rivers and headwater streams in the northwestern United States (Tyre et al. 2011). Habitat fragmentation and degradation, loss of migratory corridors, declines in water quality, and other threats have induced a long-term decline in bull trout populations across their range. In the third case study, Tyre et al. (2011) develop an adaptive decision framework for management of tributary connections to benefit bull trout in the Lemhi River Basin in Idaho. Using a patch network model that captures implicit spatial structure, they derive an optimal state-dependent management strategy and show that the optimal action is often to connect latent patches (tributaries that are occupied but unconnected), but uncertainty about the underlying ecology is quite relevant to decision making. A monitoring design could provide the adaptive feedback loop to reduce the key uncertainties, but little information is likely to accrue over a 10-y period, so the power to actually adapt to new information is low. This is an important point: that the value of adaptive management depends on two factors: having a high value of information, and having high power to acquire that information (Runge et al. 2011*b*). Tyre et al. (2011) show that framework development and initial analysis can allow evaluation of these factors before an expensive monitoring program and fully adaptive framework are put into place.

A number of lessons emerge from consideration of these case studies. First, simply framing the decision often removes the first impediment to decision making because it provides clarity about the objectives at play, the management options on the table, and the uncertainty about how the species will respond. Second, predictive modeling, even if simple in structure and based on expert judgment or sparse data, encourages transparency in the scientific understanding of the species and provides often-surprising insights about the potential consequences of management. Third, while uncertainty abounds in the management of threatened and endangered species, not all uncertainty is relevant to decision making. The uncertainty that matters is the uncertainty that would lead to different management policies, and it is useful to make sure that uncertainty matters before embarking on its reduction. Fourth, where uncertainty matters, adaptive management can provide guidance on how best to reduce the uncertainty, and balance the long-term benefits of learning against its short-term costs.

Summary

Adaptive management is one of many tools arising out of the field of decision analysis that can be of tremendous benefit to managers of threatened and endangered species. But rather than picking up an adaptive management hammer and looking for imperiled species nails, the more fruitful approach is to analyze any particular decision context, and identify the appropriate tools for the setting. In some cases, when decisions are recurrent and impeded by reducible uncertainty, the right tool will be adaptive management, but this will not always be the case. Underutilization of adaptive management for threatened and endangered species may be alleviated by thoughtful diagnosis of the impediments to decisions, by grassroots application across many scales of management, and by increasing the capacity for decision analysis within management agencies.

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