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Perspective

A three-pipe problem: dealing with complexity to halt amphibian declines

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ABSTRACT

Natural resource managers are increasingly faced with threats to managed ecosystems that are largely outside of their control. Examples include land development, climate change, invasive species, and emerging infectious diseases. All of these are characterized by large uncertainties in timing, magnitude, and effects on species. In many cases, the conservation of species will only be possible through concerted action on the limited elements of the system that managers can control. However, before an action is taken, a manager must decide *how* to act, which is, if done well, not easy. In addition to dealing with uncertainty, managers must balance multiple potentially competing objectives, often in cases when the management actions available to them are limited. Guidance in making these types of challenging decisions can be found in the practice known as decision analysis. We demonstrate how using a decision-analytic approach to frame decisions can help identify and address impediments to improved conservation decision making. We demonstrate the application of decision analysis to two high-elevation amphibian species. An inadequate focus on the decision-making process, and an assumption that scientific information is adequate to solve conservation problems, must be overcome to advance the conservation of amphibians and other highly threatened taxa.

1. Introduction

"But I must be prompt over this matter." [said Holmes.]

"What are you going to do, then?" I asked.

"To smoke," he answered. "It is quite a three pipe problem, and I beg that you won't speak to me for fifty minutes."

The Red Headed League, Sir Arthur Conan Doyle

Increasing challenges in the conservation of biodiversity have been brought about by large scale changes to ecosystems from land development, climate change, invasive species, and emerging infectious diseases. Managers tasked with species conservation often have little to no control over these processes, yet they must find ways of carrying out their work. They face several challenges in doing so, and these challenges can be of nearly overwhelming magnitude. Game et al. (2014:271) summarized it well: "*Conservation is not rocket science; it is far more complex.*"

First, in virtually all cases, managers' abilities to make predictions about future ecosystem states is limited. Socio-ecological systems are incredibly complex (Liu et al., 2007), characterized by non-linear dynamics, feedbacks, and interactions. This complicates understanding the presence and magnitude of threats as well as managers' abilities to respond effectively to threats. For scientists studying ecological systems, and managers attempting to manage them, epistemic uncertainty (Regan et al., 2002) is ubiquitous.

Socio-political complexity and uncertainty are often considerable as well (Game et al., 2014; Williams et al., 2007). It can be difficult for managers to negotiate the multi-layered legal settings in which they operate, given different levels of government, public and private landownership, mismatches between ecological and political boundaries, and a constantly shifting policy landscape. Additionally, conservation conflict continues to grow (Redpath et al., 2013) and can be daunting to manage.

Amphibians as a taxon have been hit hard by large scale changes to ecosystems. The precarious state of amphibian conservation has been well documented (e.g., Stuart et al., 2004). And yet, research focused on describing and understanding the threats to amphibian populations far outpaces research focused on actions that managers might take in the face of these threats. This is perhaps particularly true for emerging threats such as climate change and disease (but see Canessa et al., 2018; Canessa et al., This Volume; Converse et al., 2017; Garner et al., 2016; Gerber et al., 2018; Scheele et al., 2014; Shoo et al., 2011; Woodhams et al., 2011). Managers trying to conserve declining amphibians –

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particularly those affected by emerging threats – often have few management actions available to them.

Finally, guidance – in the form of agency mandates or policy – is often vague. For example, the Organic Act of 1916 directs the U.S. National Park Service (NPS) to manage protected areas "…*which purpose is to conserve the scenery and the natural and historic objects and the wild life therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations.*" Each resource management problem faced by this agency must be considered given this directive. However, while it provides general direction, it does not specify resource management objectives, nor how achievement of objectives will be assessed, nor how to balance tradeoffs between objectives. This is generally true of agency mission statements and supporting policy – they emphasize overarching values while leaving specifics to be defined for each problem.

In sum, managers attempting to mitigate species declines work in environments with some or all the following characteristics: (1) complex ecological systems about which they know relatively little; (2) little control of threatening processes; (3) tremendous socio-political complexity and, frequently, conflict; (4) few technological solutions to apply within their scope of control; and (5) vague guidance in agency policy. Against this backdrop, it is not surprising that some managers feel stymied.

As applied ecologists, we are regularly approached by managers who face challenging conservation problems. We are asked for help in resolving uncertainty about system function under the assumption that information will point the way out of complexity toward action. However, in many cases, research appears to us to be a second-order consideration. Launching into research without having a clear idea about how that information will be used can be unhelpful, and even harmful if it causes a needless delay and uses precious resources (Grant et al., 2013; Lindenmayer et al., 2013; Sterrett et al., 2019). Martin et al. (2012) provide, for example, a cautionary tale about the extinct Christmas Island pipistrelle (*Pipistrellus murrayi*). The decline of this species was known and monitored from 1994 to 2009, with multiple research efforts proposed or undertaken, and only in the several months preceding the last detection of the species was any management attempted.

We therefore frequently find ourselves recommending that managers stop before undertaking research and instead focus on developing a framework that will help them organize their thinking and determine how to act, with or without further information. To accomplish this, we have found that a decision-analytic framing of conservation problems can be game changing. A conservation problem can only be addressed once a decision maker, who has the power to commit resources to solving the problem, decides how to use those resources. In other words, a conservation problem suggests that one or more decisions must be made, and it is deciding which course of action to choose that is the important but challenging task. Unfortunately, all the scientific information in the world cannot tell a manager what course is best, if that information is not placed within a cognitively tractable framework.

This is the essential basis of Sherlock Holmes' three-pipe problem – when faced with a complex and pressing need to undertake a course of action, it is prudent to stop and think hard about the decision of how to act. An incorrect or inadequate conceptualization of a conservation problem risks identifying the right solution to the wrong problem, prioritizing research that does not address management needs, and ultimately failure to attain conservation objectives.

Our goal here is to inspire managers and their scientist partners dealing with amphibian declines to move through complexity toward action. We begin by explaining what is meant by "framing" a decision problem. We then demonstrate the process of developing a decision-analytic framing for declining amphibian populations and of carrying through with the decision analysis to identify preferred management alternatives through two case studies. We discuss how decision-analytic processes led to advances and breakthroughs in thinking in these two case studies. While we do not argue that decision analysis can make hard problems easy, we do argue that they can make seemingly impossible problems tractable, so that progress can be made toward conservation, before it is too late to save species.

2. Framing decision problems

The field encompassing decision analysis is large (e.g., Gregory et al., 2012; Keeney, 1992). But most fundamentally, decision analysis provides, first, a roadmap for deconstruction of a decision and development of a more thorough cognitive grasp of the situation, and second, a set of tools for dealing with challenges in formal decision making. The components of a decision include (1) the definition of the decision problem; (2) management objectives; (3) management alternatives; (4) models for making predictions about the impact of management alternatives on management objectives; and (5) a solution, or optimization, algorithm (Converse et al., 2013; Gregory et al., 2012).

Perhaps surprisingly to those not familiar with decision analysis or conservation management more broadly, the dominant challenge is often not in component (4) – models and predictions, the component of most interest to scientists – but instead is in component (1) – defining the decision problem. Consider the theoretical example of a threatened amphibian living at high elevations across an area spanning 10,000 s of km^2. It is quickly declining in the wild and managers of the captive population have not yet determined how to breed it in captivity. Several challenging questions will immediately occur to a decision analyst asked to assist with this problem:

- Who is the decision maker, or decision makers? A species with a large range will likely occur on a patchwork of land ownerships, and multiple government agencies and private landowners may be involved.
- What is the decision to be made? Is it a question of devising a strategy to improve captive husbandry as insurance against apparently imminent extinction in the wild? Or figuring out how to arrest the decline in the wild? Or deciding whether to provide a higher level of legal protection to the species? Or all these simultaneously?
- What forces triggered the need to reach a decision? How do these triggers weigh on the decision-making process, legally or otherwise?
- What is each decision maker trying to achieve through management of the system, and what constraints – legal or practical – influence the feasibility of alternatives?
- Who are the stakeholders and what are their values? How can they be engaged, and what tradeoffs are likely to be unacceptable to them?
- When must the decision be made? Is the goal to decide what to do this year, or what to do each year for many years to come?
- What is the spatial scale of the decision? Does it encompass the entire range of the species, or some portion of the range controlled by a given decision maker?
- Is there important scientific uncertainty? Is the decision maker able and willing to invest in reducing uncertainty before deciding, or in monitoring to reduce uncertainty over time, if it is warranted (sensu Canessa et al., 2015; Runge et al., 2011; Williams et al., 2011)?

The answers to these questions will influence all subsequent steps, including gathering needed scientific information, designing a decision-analytic process, and solving the decision problem.

3. Case studies

We present case studies for decision framing in two high-elevation amphibian populations in the United States. These focal species come from different environments but both are at risk of decline and local extirpation, or even extinction, in the foreseeable future (La Sorte and Jetz, 2010; Lawler et al., 2009). We emphasize the process and value of developing a prototype framework, with an emphasis on defining the decision problem. More details are available for each case study elsewhere (Converse et al., 2017; Gerber et al., 2018; Grant et al., 2014).

3.1. Shenandoah salamander case study

3.1.1. Defining the decision problem

The federally endangered Shenandoah salamander (*Plethodon shenandoah*) is found only in Shenandoah National Park (hereafter Shenandoah), Virginia, USA, on the three highest mountaintops, and is restricted to north-facing slopes above 850 m asl. NPS is primarily responsible for management of the salamander in consultation with the U.S. Fish and Wildlife Service and the State of Virginia, and they recognized a need to decide whether to initiate management to reduce the extinction probability for this endemic salamander. Extinction risk was thought to be related to two principle threats: competition with the sympatric red-backed salamander, and climate change. Competition was the dominant hypothesis (Jaeger, 1970), and the recovery plan was written in 1994 with this threat principally in mind. More recent research suggests that climate change is reducing the suitability of high-elevation habitat via increases in temperature and decreases in precipitation (Grant et al., 2018). While management plans at Shenandoah are developed with 5-year planning periods, decisions may be made every year; a 60-year time horizon was considered appropriate for this problem. NPS is tasked with ecosystem management, so potential tradeoffs with other elements of the system were an important consideration. NPS wanted to maintain the historic range of the species. Whether the extinction risk from competition was sensitive to a shift in abiotic conditions under climate change was a considerable uncertainty.

There were three main sources of policy guidance for this decision. The Endangered Species Act (1973) obligates the Park to conserve and restore federally listed species and the ecosystems upon which they rely. The Organic Act (1916) obligates the preservation of all NPS resources, and to provide for public enjoyment of these resources in a manner that will leave them unimpaired for future generations. And finally, the management policies of the NPS direct NPS to manage habitats for threatened and endangered species to "maintain and enhance their value for the recovery of the species" (NPS, 2006). Meeting the intent or requirements associated with each of these obligations simultaneously requires careful planning and input from multiple NPS staff members.

In NPS, resource management decisions are made by the Park superintendent, under recommendations from the biologist to the chief of resources, and also considering national NPS policy. Participants in the decision process included the biologist, the chief of resources, the superintendent, and two NPS policy experts. They recognized that there was sparse and conflicting information on the ecology of the species, virtually no information on the status of the species since the early 1980s, and no information on the relative effects of competition and climate on extinction risk. Because NPS recognized legal requirements for stewardship of the species under the Endangered Species Act, and for high-elevation habitat (home to other threatened, endangered, and endemic species) under the Organic Act, a principle motivating question had been, "Should NPS consider active management for this species"? NPS would consider active management if two conditions were met: (1) the species was at risk of extinction and (2) the cause of endangerment was human-induced (as opposed to a natural process of senescence of the habitat, or extinction via natural biotic processes, i.e., competition). Whether either of those conditions was met was unknown, resulting in significant information gaps. Coincidentally, a memo from the Director of the NPS provided latitude for NPS to implement active management when climate change threatened natural processes, thus enabling NPS to consider their decision in the context of future extinction risk under climate change.

3.1.2. Objectives

NPS identified four objectives that were of fundamental importance when considering active management; 1) maximize persistence of the salamander in its current range; 2) maximize public acceptance of any management action; 3) minimize cost of active management; and 4) adhere to NPS policies. This last objective was comprised of multiple sub-objectives: (4a) minimize human influence and management on natural processes; (4b) maximize use and enjoyment of park resources by visitors; and (4c) minimize negative impact on other native species within the high-elevation ecosystem in which the salamander resides.

The precautionary principle is often cited in resource management problems when there is risk of irreversible harm (Gregory and Long, 2009). Essentially, invocation of the principle suggests aversion to certain types of risks. Estimating the potential risk is the realm of science, while specifying risk tolerance is the realm of policy. Clarity is needed in both. In this case, there was a divergence in defining preferences among the objectives between U.S. Fish and Wildlife Service and NPS; both entities recognized joint responsibility for management of the salamander. Because minimizing negative impact to the high-elevation ecosystem was a fundamental objective for NPS, this policy objective resulted in the NPS invoking the precautionary principle with respect to decline of the ecosystem. This reflected the concern that active management may harm other components of the ecosystem even if it would be beneficial to the salamander. In contrast, because U.S. Fish and Wildlife Service considers only the endangered species, they focused only on the salamander persistence objective, and invoked the precautionary principle for the extinction of the salamander. For NPS, existing policy was cited to support the preference for 'ecosystem management' where no single species is given precedence over the natural processes within the ecosystem (and especially because interspecific competition is a natural process). Thus, while objectives were developed and recognized jointly by the group, the relative importance assigned to each differed by agency.

3.1.3. Alternatives

Alternatives were considered in two steps. Scientific experts first considered alternatives that could target three aspects of the system: management of the habitat to increase the likelihood of Shenandoah salamander adaptation to potential climate change, management to reduce the effect of interspecific competition from the red-backed salamander, and reduction of human disturbance. Then, in a second step (and with experts in NPS policy), actions were evaluated for their adherence to NPS policy. The resulting list of actions included management of habitat, such as manipulating forest structure; manipulating soil and rock substrate; elimination of direct human activity (i.e., relocate or close trails); humidity and temperature control (e.g., via shade cloths, sprinkler systems); and actions targeted at species directly (e.g., assisted relocation, reduction in population density of the competing species).

3.1.4. Models

Alternatives are evaluated for each objective with a model or set of models. For the Shenandoah salamander, a two-species conditional occupancy model (Richmond et al., 2010) was used to estimate local extinction and colonization probabilities from the available field data. These rates were used to forecast the future probability of extinction of the Shenandoah salamander from its high-elevation range. The effects of various climate scenarios on the probability of persistence after 60 years were evaluated using a simulation model. Three climate change scenarios for summer were considered: (1) no climate change, (2) warmer and wetter, and (3) warmer and drier. Also, scenarios for competition and no competition on the occupancy dynamics of the Shenandoah salamander were considered. When data were not available to provide empirical estimates, the group provided estimated values, though no formal elicitation method (sensu Martin et al., 2011) was used. While the probability of salamander persistence was informed by the simulation model, the performance of the alternatives on the other objectives was provided directly by participants.

3.1.5. Decision analysis and outcomes

In a multiple objective problem, the optimal action is that which provides the most favorable tradeoff among objectives. Tradeoffs can be evaluated by accounting for the relative importance of each objective i specified as a set of objective weights (w_i) that are reflective of decision-maker values. In this problem, the decision maker solicited input from staff familiar with the high-elevation system, as well as NPS policy specialists that could provide input on how NPS policy should guide weighting. Global weights (Monat, 2009) were elicited from the NPS staff. Each staff member chose the objective most important to them, set the value for that objective equal to 1, and then determined the value of all other objectives relative to that. Weights were standardized to sum to 1 across all objectives, and then averaged across all participants. Weights can be used to create an overall score for an alternative, as a weighted average of the standardized performance of an alternative on each objective (i.e., the Simple Multi-Attribute Rating technique; Edwards, 1977).

The relative weight given to the salamander objective was 0.3, indicating that the decision maker valued persistence of the salamander, relative to the other objectives, slightly more than if the weights were allocated equally among the four objectives (i.e., $w_i = 0.25$ for all i). The 'adherence to NPS policy' objective was given a similar weight (0.31), while 'maximize public acceptance of any management action' and 'minimize cost of active management' objectives were similarly weighted ($w_{public} = 0.19$; $w_{\text{cost}} = 0.20$). These weights reflected the tension in NPS policy between allowing natural ecosystem processes and preservation of the federally endangered species within the Park.

Under the current climate scenario, active management to improve the persistence probability for the salamander was not supported, particularly because it performed worst on the adherence to park policy objective, which considers extinction of the salamander to result from natural processes (and seen to fit within the mandate set out in NPS policy documents). However, active relocation of the Shenandoah salamander to more suitable habitats was the best-supported action under future climate change scenarios (particularly under a warmer and drier future).

While no active management decision was finalized following the workshop, NPS recognized that there was indeed a need to consider active management for the salamander. Work is ongoing to evaluate controls on the range-edge and dynamics (Grant et al., 2018; Amburgey et al., 2019), to evaluate support for competition as a driver of extinction risk, to determine habitat associations that may improve the identification of management options, and to understand the value of the remaining uncertainties to an active management decision. This will be accomplished via a Science Panel Review, a formal and necessary step for implementing active management decisions in National Parks.

3.2. Boreal toad case study

3.2.1. Defining the decision problem

The southern Rocky Mountain population of the boreal toad (*Anaxyrus boreas boreas*; hereafter SRMP) – distributed historically in Wyoming, Colorado, and New Mexico, but now confined to Wyoming and Colorado – has declined precipitously in the last 40 years (Carey et al., 2005). Local extirpations have been linked to the pathogenic chytrid fungus *Bd* (*Batrachochytrium dendrobatidis*; Muths et al., 2003). The first conservation plan for the SRMP was produced in 2001 by a coalition of federal and state government agencies (Boreal Toad Conservation Team; hereafter Boreal Toad Team), led by the Colorado Division of Wildlife (now Colorado Parks and Wildlife; Loeffler, 2001).

In 2015, a decision from the U.S. Fish and Wildlife Service regarding a petition to list the eastern boreal toad (which encompasses the SRMP) under the Endangered Species Act was on the horizon. The Boreal Toad Team, in the face of ongoing declines and the prospect of increased regulation if the SRMP was federally protected, undertook a process to develop a revised recovery plan. In developing this revised plan, the Boreal Toad Team wanted to identify the management alternatives that would be most effective in recovering boreal toads in the SRMP. At the same time, there was concern that funds for management would be limited. The SRMP occurs primarily on public lands, and other users of those lands could be affected by management decisions; these users needed to be considered given agency mandates. There was a desire to develop a plan that would be applicable throughout the historical range of the SRMP and would guide actions taken on an annual basis for the subsequent 5–10 years or more. While the Boreal Toad Team was interested in considering a wide range of potential actions, substantial uncertainty about the effectiveness of available actions weighed heavily on the decision.

3.2.2. Objectives

The Boreal Toad Team identified 4 management objectives. The first three of these were related to the Three Rs of conservation biology: resiliency, redundancy, and representation (Shaffer and Stein, 2000). These included 1) increase the probability of persistence of the SRMP population over a 50-year time horizon; 2) maximize the number of mountain ranges that have breeding populations of Boreal Toads (of those ranges in the SRMP that had breeding populations historically); 3) maintain the genetic diversity that exists in the SRMP; and 4) minimize cost of Boreal Toad management to signatory agencies. Because genetic diversity (objective 3) is difficult to predict and is likely strongly related to objectives 1 and 2, only objectives (1), (2), and (4) were formally accounted for within the process.

3.2.3. Alternatives

Strategy-based alternatives arise in many conservation contexts where management is not limited to a single action, but to a suite of actions that could be implemented. Solving the decision problem requires determining which set of actions to take. There were a total of 35 alternatives evaluated by Gerber et al. (2018), and these were composed of combinations of actions in 3 broad categories: disease management actions (e.g., limitation of public access to breeding sites to reduce the risk of *Bd* being introduced), habitat management actions (e.g., site fencing to reduce disturbances), and reintroductions (all reintroductions were assumed to involve releases to sites over 10 consecutive years, with reintroduction cohorts composed of wild-produced eggs reared to tadpole stage in a hatchery).

3.2.4. Models

A predictive model was developed based on a two-species occupancy framework (Mosher et al., 2018). Each site (125 wetland complexes across 11 mountain ranges in Wyoming, Colorado, and New Mexico), was modeled as occupying one of 4 states: TB = the toad is present, *Bd* is present; T0 = the toad is present, *Bd* is absent; 0B = the toad is absent, *Bd* is present; and 00 = the toad is absent, *Bd* is absent. For toads, "present" was defined as breeding (presence of egg masses at some point during breeding season). Sites could change state from year to year, based on two parameters: local extirpation probability (ε) and local colonization probability (γ). These probabilities, for toads and for *Bd*, may depend on the presence of the other organism, such that ε^{TB} is the probability that toads go extinct in the presence of *Bd* while γ^{B0} is the probability that *Bd* colonizes a site in the absence of the toad.

The predictive task, within this framework, is to determine how management actions will influence these transition parameters at any site. Reintroduction actions are distinct in that they influence the state of the site directly, rather than the transition probability, i.e., a reintroduction action has some probability (the success probability for the reintroduction action) of causing a site to change from state 00 to T0 or from state 0B to TB.

A fundamental challenge of many endangered species management problems is that managers are often contemplating actions about which there are no empirical data. This is the nature of endangered species management; if existing actions had been successful, the species would no longer be endangered or at least recovery would be in sight. If a species is still endangered, this suggests that new and untried actions might be contemplated. When empirical information is absent, expert judgment can be a powerful source of information (Martin et al., 2011; Runge et al., 2011). Gerber et al. (2018) describe the process of eliciting information from a panel of experts using the 4-point elicitation process of Speirs-Bridge et al. (2010) to develop estimates for the effects of management actions on the toad and *Bd* transition parameters. The 4-point elicitation method allows for quantification of expert uncertainty, and both within- and between-expert uncertainty were incorporated into the predictive model. This allowed for the prediction of system state (i.e., which of the 125 sites would be occupied 50 years in the future) and the uncertainty around it, as a function of a given alternative, for each of the 35 alternatives considered.

3.2.5. Decision analysis and outcomes

A challenge in decision analysis when multiple management objectives are identified is how to negotiate tradeoffs between objectives. A clear tradeoff often exists, for example, between risk of extinction and cost of management: dedicating more resources to management often improves the prospects for an endangered species. A suite of approaches fitting within the general framework of multi-attribute value theory (Keeney and Raiffa, 1976) can be used to solve multiple objective problems. These approaches generally involve evaluation of tradeoffs by working with decision makers to assign weights to different objectives; these weights are indicative of the relative importance of the objective to the decision maker. Weights vary by decision maker and decision context.

Rather than determine specific weights for persistence, geographic spread, and cost in the context of the decision problem, given the large set of agencies in the Boreal Toad Team, Gerber et al. (2018) strove to identify alternatives that performed well across a wide variety of weights. In other words, they looked for alternatives that would appeal to decision makers with a wide variety of values regarding the relative importance of the three identified management objectives. To accomplish this, they considered weights (w_i, where $w_i \in [0,1]$ and $\sum_{i=1}^{3} w_i = 1$) for the $i = 3$ objectives, and then considered all possible permutations of sets of weights. For each permutation, they identified the optimal alternative based on

$$optimal\ action = argmax_j (w_1 x_{1,j} + w_2 x_{2,j} + -w_3 x_{3,j})$$

where $x_{1,\ j}$ is the (standardized) performance of alternative j with respect to persistence, $x_{2,\ j}$ is performance with respect to geographic spread, and $x_{3,\ j}$ is performance with respect to cost. Note the negative sign on cost: higher values of persistence and geographic spread were preferred, while lower values of cost were preferred.

Gerber et al. (2018) found that one alternative performed best over 66% of the weight permutations. The optimal strategy included the maximum number of reintroductions, actions to reduce *Bd* colonization, and actions to increase toad colonization and persistence. Under this strategy, the expected decline, over 50 years, of toad-occupied breeding sites and mountain ranges was 21% and 17%, respectively. By comparison, under a status quo strategy, the expected decline in toad-occupied breeding sites and mountain ranges was 53% and 53% over 50 years. The decision-analytic process, therefore, indicated that, under a broadly palatable management alternative, the rate of decline could be more than halved relative to the status quo.

In late 2017, the U.S. Fish and Wildlife Service issued a finding that the eastern population of the boreal toad (inclusive of the SRMP) was not warranted for listing under the Endangered Species Act (U.S. Fish and Wildlife Service, 2017). This decision was based in part on the work accomplished by the Boreal Toad Team in proactively engaging in the decision analysis to understand the previous 20 years of information accumulation, and to formally identify management strategies going forward.

3.3. Value of decision framing

Each case study offers insights into the value of decision framing. In both cases, substantial complexity existed such that decision makers were finding it difficult to move forward. The benefits of decision framing can be hard to see from the vantage point of a completed decision process, and so it is useful to look back and consider where the problem was before framing was undertaken. The insights gained can be useful in developing decision frameworks for related case studies.

3.3.1. Shenandoah salamander case study

For NPS, this decision framing exercise for the Shenandoah salamander led to the insight that the management problem is tractable, and clarified thinking about the objectives, and tradeoffs, that must be considered in an active management plan. Importantly, NPS initially wanted to know whether management was necessary for the salamander, which would be indicated by observed declines and a forecast for future extinction. Estimating population status and trends is squarely within the realm of science; however the decision analysis NPS undertook allowed consideration of the course of action that could be taken to reduce the extinction risk, while considering other management objectives. This decision framing provided context for the extinction risk forecasting. Specifying objectives helped NPS recognize real constraints (i.e., scientific uncertainty of the species ecology), and reduce the influence of perceived constraints (i.e., limitations of NPS policy on initiating active management) on evaluating the potential actions. The decision framing allowed NPS managers to consider NPS policy in light of specific objectives, alternatives, and values weights (representing preferences among the fundamental objectives). In discussing potential alternatives, the group separated the steps of generation and evaluation for feasibility and compliance with policy, which enhanced creativity in finding solutions. In part because terrestrial salamander management is not widely undertaken, and little was known about the distribution and ecology of the species, generating creative ideas may have been easier than for problems with a more mature knowledge base. However, the lack of contemporary knowledge of the status and behavior of the system was a sticking point in the problem framing. Listing and discussing the perceived uncertainties was necessary to clarify which were expected to be important to the decision (i.e., those that would change the selection of alternatives) and those which were important to the process with respect to NPS policy (i.e., whether extinction risk was human vs. natural). NPS requires a science panel to evaluate the uncertainty in evidence used to support active management. In the case of the Shenandoah salamander, significant uncertainty remains in how the system functions. Despite the uncertainty, the decision analysis found that active management was warranted. A formal value of information analysis (e.g., Runge et al., 2011; Williams et al., 2011) will be completed, and will help to quantify the costs of reducing uncertainty, both in terms of time (i.e. years available to learn) and dollars (if monitoring or experiments can be proposed to reduce uncertainty). Following this work, NPS will have specific recommendations for moving forward with management actions to conserve the salamander.

3.3.2. Boreal toad case study

For the SRMP problem, problem framing facilitated an emphasis on action despite uncertainty. The predicted effectiveness of possible solutions to the mortality associated with pathogenic chytrid was a substantial source of uncertainty. Recognizing, but not being stymied by, this uncertainty was key to identifying a management alternative that had the potential to substantially slow declines. When the problem was originally presented to SJC, it was presented as a problem of developing recovery criteria. Developing such criteria is an important part of decision making, however, it is only one step and will not, by itself, allow for a decision. By completing, and then pushing beyond identification of objectives, there was a greater focus on action. The process of developing objectives and measures was allotted substantial time, requiring more than one full day of discussion. However, this challenge was relatively small compared to the challenge of developing a set of alternatives, for at least two reasons. First, for species impacted by *Bd*, there are no "silver bullet" actions. Second, alternatives were not – as may be thought at first consideration – single actions. Instead, they were collections of actions. Through the decision-analytic process, this became apparent to the Boreal Toad Team, and a set of alternatives composed of a combination of actions including some that were relatively well understood and some that were more speculative encouraged creativity. Finally, this problem seemed initially daunting because of a lack of empirical information. While there is great uncertainty, biologists working in the system do have some ideas about what might work and what might not. The formal 4-point expert elicitation process indicated that there was relative cohesion among experts in the expected effectiveness of actions, while also bounding the uncertainty. Though a formal value of information analysis (Canessa et al., 2015; Runge et al., 2011; Williams et al., 2011) has not yet been completed, the process suggested that directed research on the effectiveness of management actions would be informative for future decisions. However, the analysis also suggested that action should not be delayed until more research is completed. These two findings together support development of an adaptive management program (Canessa et al., 2016; Runge, 2013; Walters, 1986) to guide management of this system. Finally, identification of a management alternative that was robust to a range of objective weights was powerful because it allowed for each of the Boreal Toad Team member agencies to be reasonably accommodated in the identification of a solution.

4. Discussion

We have focused here on demonstrating the value of framing conservation problems as decisions. The goal of framing is to make the complexity of a decision cognitively tractable. At the least, framing a problem and conducting a decision analysis should move managers in the direction of better understanding the problem and toward identification of a reasonable set of plausible alternatives. Framing the problem can be the biggest challenge, and the challenge of framing gets bigger as problems become more complex.

While we began by noting that scientific uncertainty in difficult conservation problems is often what nominally motivates managers to seek technical assistance, decision framing can be valuable regardless of whether uncertainty is a major challenge. An understanding of what predictions are needed, and at what level of complexity and detail, arises from the decision framing. Even when information is relatively rich, prediction will be more difficult and less accurate if carried out implicitly without formalized predictive models. And once information is organized in predictive models, it is often the case that decisions involve challenges other than uncertainty, such as the need to wrestle with difficult tradeoffs or the need to solve a challenging optimization. We would distinguish cases when formal decision-analytic processes are needed based on the difficulty, complexity, and importance of the decision, not based on the degree of information available.

4.1. Undertaking decision analyses

We have found a rapid prototyping approach useful for framing seemingly intractable problems (Garrard et al., 2017). Rapid prototyping is a process whereby an individual or group rapidly develops all components of a decision framework, with frequent assessment of its applicability to the problem, to evaluate the viability and realism of the framing, and assess whether it will be useful in informing the decision. An intensive workshop structure can be useful, in which the team can immerse themselves in the problem. Becoming adept at decision analysis and rapid prototyping requires both study and practice. Fortunately, there are increasingly large and influential training programs available to grow capacity – both familiarity and advanced expertise – in decision analysis for conservation (e.g., U.S. Fish and Wildlife Service's National Conservation Training Center; https://nctc.fws.gov/courses/catalog/guide/index.html; accessed 7 Oct 2018). Some general texts are also available to provide guidance about the practice of decision analysis for natural resource management problems (Burgman, 2005; Conroy and Peterson, 2013; Gregory et al., 2012; Runge et al., Accepted).

Anyone can develop the broad outlines of a decision-analytic framework if they keep two key concepts in mind. First is problem decomposition. That is, one must work to explicitly separate and recognize the components of a decision problem (i.e., problem definition, objectives, alternatives, models, and an optimization or solution method). Second is a focus on values (Keeney, 1992), that is, the recognition that management objectives must be paramount in driving the decision-making process. Ultimately, decision making is a process of figuring out the correct path to reach some desired future state. It is therefore critical above all else to clearly define that desired state and allow that definition to guide the decision.

4.2. Remaining challenges

While we find that decision framing can help clarify resource management problems, and identify challenges to implementing a management plan, sometimes there are few effective management actions in the manager's toolkit. This speaks to the importance of creativity in solving conservation challenges (Aslan et al., 2013). There are several practices that encourage creativity. First, we maintain a strict separation between generation of action ideas and assessment of actions. The tendency to immediately judge actions that are perceived to be either unknown or ineffective is strong and can restrict participant's willingness to share new ideas. Second, we encourage individual work. Getting the best out of a group requires recognizing that participants will be differentially assertive in group settings. Thus, we will often ask participants to work independently to create a list of ideas before being asked to share their list. Third, individuals in a group may have different modes of thinking, so providing for multiple idea generation approaches, including discussion and visual mapping, can expand the number and breadth of potential actions (Howard et al., 2008). Finally, encouraging multidisciplinary membership on problem-solving teams can be useful. For example, more teams focused on amphibian conservation in the face of *Bd* could include mycologists or experts in treatment of fungal diseases in humans. Conservation management can benefit by being open to other knowledge domains (Game et al., 2014).

Once creative solutions are posed, it is often necessary to overcome cognitive biases to implement those potential solutions. There is a strong 'status quo' bias (Samuelson and Zeckhauser, 1988) toward continuing what has been done in the past. This, and biases in perception of risk (Slovic, 1987), are associated with resistance to trying previously untried management actions. However, through elicitation of expert judgment, the uncertainty can be quantified, and then the risks of applying an untried action can be accounted for in the analysis (Burgman, 2005). Furthermore, once a set of alternatives is posed, there is opportunity for productive research inquiry, allowing for research into the effectiveness of management actions (Ferraro and Pattanayak, 2006; Schmidt et al., 2019) or adaptive management (Canessa et al., 2016; Runge, 2011). The resulting information can be used to inform future actions directly, so long as the decision framework has been developed.

4.3. Moving forward

Using a decision-analytic framing for a conservation problem has the potential to help solve seemingly intractable problems. Specifically, this approach can help overcome the struggles associated with hugely complex conservation problems by providing a framework that is cognitively tractable. It should not be the goal in analyzing a decision to strive for a pre-conceptualized notion of completeness in the analysis. Instead, the focus at every step in the process should be on whether the decision maker can make a better decision with additional analysis, and whether that additional analysis is worth the required investment. It should also be recognized that a value of analysis is formalizing the process to communicate it to others and be able to make a better decision the next time the same or similar problem appears. A formal analytical framework can be built upon and improved over time, allowing all subsequent decisions that might rely on the framework to be improved as well.

Ultimately conservation is about 'moving the needle' by understanding who has the power and resources to do something to change the status of an at-risk species and helping that decision maker to make the best decision possible. Failing to grapple with this fundamental challenge, and instead becoming stuck in the face of complexity, or using research as a displacement activity, has the potential to be harmful when action is needed.

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Competing interests

The authors declare no competing interests.

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