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Natural Resource Stewardship and Science

Management and Monitoring of the Endangered Shenandoah Salamander Under Climate Change

Workshop Report 10-12 April 2012

Natural Resource Report NPS/SHEN/NRR—2014/867

ON THE COVER
Shenandoah salamander (*Plethodon shenandoah*)
Photograph by: Ann and Rob Simpson

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E.H.C. Grant[1], J.E.B. Wofford[2], D.R. Smith[3], J. Dennis[4], C. Hawkins-Hoffman[5], J. Schaberl[2], M. Foley[6], M. Bogle[2]

[1]USGS Patuxent Wildlife Research Center
SO Conte Anadromous Fish Laboratory
Turners Falls, MA

[2]National Park Service
Shenandoah National Park
3655 US HWY 211E
Luray, VA

[3]USGS Leetown Science Center
Kerneysville, WV

[4]National Park Service
Natural Resource Stewardship and Science
Washington, DC

[5]National Park Service
Natural Resource Stewardship and Science
Fort Collins, CO

[6]National Park Service
NE Regional Office of Scientific Studies
Boston, MA

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Abstract

Here we report on a structured decision making (SDM) process to identify management strategies to ensure persistence of the federally endangered Shenandoah salamander (*Plethodon shenandoah*), given that it may be at increased extinction risk under projected climate change. The focus of this report is the second of two SDM workshops; in the first workshop, participants developed a prototype of the decision, including problem frame, management objectives and a suite of potential management strategies, predictive models to inform the decision and link alternatives with the objectives to identify potential solutions, and identified data needs to reduce key uncertainties in the decision. Participants in this second workshop included experts in National Park Service policy at multiple administrative levels, who refined objectives, further evaluated the initial management alternatives, and discussed policy constraints on implementing active management for the species and its high-elevation habitat. The conclusion of the second workshop was similar to that of the first: the current state of information and objectives suggest that there is some value in considering active management to reduce the long-term extinction risk for the species, though there are institutional conservative policies to implementing active management at range-wide scales. The workshop participants also emphasized a conservative NPS management philosophy, including caution in implementing management actions that may ultimately harm the system, a stated assumption that ecosystem changes were “natural” unless demonstrated otherwise (therefore not warranting active management to mitigate), and a need to demonstrate that extinction risk is tied to anthropogenic influence prior to taking active management to mitigate specific anthropogenic influences. Even within a protected area having minimal human disturbance, intertwined environmental variables and interspecific relationships that drive population trends challenge our ability to demonstrate direct links with (anthropogenically influenced) climate change and the decline of a species. Thus while this policy may reduce the potential for injurious management, it may also necessitate extraordinary resources to reduce uncertainty regarding fundamental drivers of species decline prior to taking action.

Introduction

Even in protected areas, climate change is presumed to threaten high-elevation biota (Lawler et al. 2009, 2010, La Sorte and Jetz 2010, Forero-Medina et al. 2011a). An assessment of the impacts of climate change is required for efficient spending of funds, suitable management of rare and endangered species, and effective conservation of National Park Service biological resources. National Park Service managers must choose among management actions that might mitigate the potential negative effects of climate change. The Shenandoah salamander (*Plethodon shenandoah*) is a federally endangered species that is endemic to Shenandoah National Park (SHEN) and that may be sensitive to climate change. Resource managers at SHEN are developing a management plan with respect to *P. shenandoah*. Such a plan should anticipate the effects of climate change on the species, limit active management interventions, and be sensitive to other aspects of the high-elevation ecosystem.

The ultimate goal is to develop an iterative decision process that could be used for managing *P. shenandoah* and that can be updated with information from a monitoring program. To gain insight into various management options in our initial modeling effort, we framed the problem to decide among a restricted set of management alternatives when consequences of that decision accrue over a 60-year period. In addition to benefiting conservation of Shenandoah salamander, this project could also provide a template for assessing climate change impacts and potential management actions on other high elevation salamander species, such as the federally threatened Cheat Mountain salamander (*P. netting*), or the rare Weller’s (*P. welleri*) and Peaks of Otter (*P. hubrichti*) salamanders.

Background

Ecological Context

The federally endangered Shenandoah salamander (*P. shenandoah*) is found only within the boundaries of SHEN. The entire potential range of the species consists of approximately 1 - 6 square kilometers of high elevation forested habitat, distributed across three mountain peaks (Highton and Worthington, 1967; Jaeger 1970, 1971$_{a,b}$; Carpenter et al., 2001). It is believed that *P. shenandoah* has become restricted by competition with the red backed salamander (*Plethodon cinereus*; Jaeger 1971$_{a}$, 1980), which appears to have expanded upslope from the lowlands during a changing climate since the Pleistocene (Highton and Worthington, 1967). *P. shenandoah* presence is strongly influenced by elevation and aspect, presumably in relation to temperature and moisture gradients and associated central and southern Appalachian high elevation forest types (Jaeger, 1971$_{b}$). Forest habitat has been further subdivided into a categorical variable, 'talus type,' which integrates vegetation cover, soil depth and exposed rock cover, and includes variation in temperature and humidity gradients (Jaeger 1971$_{b}$). Talus type is hypothesized to be a proximate variable for temperature and humidity conditions to which a salamander may ultimately be responding, and has been used to describe the realized niche of *P. shenandoah* (Jaeger 1971$_{b}$).

Legal, Regulatory, and Political Context

The Endangered Species Act (1973) obligates the Park to conserve and restore federally listed species and the ecosystems upon which these species rely, and to consult with the US Fish and Wildlife Service (FWS) on federal actions that may affect those species. The US Fish and Wildlife Service completed a recovery plan for *P. shenandoah* in 1994. However, this recovery plan provides vague recovery goals (FWS 1994), presenting a major challenge for efforts to recover the species. When the plan was written, the main hypothesis for the limited distribution of the species was competition with the *P. cinereus*. This hypothesis led to adoption of the following recovery objective (citing pg. 13 of FWS 1994):

"Due to the long-term threat of extinction of the Shenandoah salamander through interspecific competition with the red-backed salamander, it is not possible to establish criteria for reclassifying or delisting *Plethodon shenandoah* in the foreseeable future. It is not anticipated that this situation will change, unless future studies of the relationship between *Plethodon cinereus* and *P. shenandoah* indicate that such change is warranted, or additional population discoveries indicate that *P. shenandoah* is much more abundant than previously believed. The recovery objective for this species is, therefore, stabilization of known populations by minimizing human impacts on the Shenandoah salamander."

As defined via this plan, without eliminating the presumed competition-induced extinction risk or discovering a much larger species distribution, recovery is essentially unattainable. While the plan was written before climate change was identified as a driving factor for human-induced changes to the distribution of high-elevation species, in particular, our current understanding is that climate change is potentially an important determinant of extinction risk for this species (LaSorte and Jetz 2010, Lawler et al. 2010, Chen 2011).

The National Park Service Organic Act (1916) obligates the conservation of all National Park resources and to provide for public enjoyment of these resources in a manner that will leave them unimpaired for future generations. Interpretation of this act has led to a conservative policy approach when it comes to intervention or management actions targeting natural resources. As such, the conceptual framework adopts the expectation that a decline (or projected future decline) in a population is natural, while evidence must be sufficient to demonstrate that a decline is human-induced before active management is supported. As such, human influence on population processes must be demonstrated or be the widely accepted model before a park is likely to intervene in processes that are otherwise presumed to be “natural”. However, the Management Policies of the National Park Service directs NPS to manage habitats for threatened and endangered species to “maintain and enhance their value for the recovery of the species” (NPS 2006). When the causal factors behind a rare species decline are not understood to be anthropgenic versus “natural”, these two policy positions may be in conflict.

New guidance has been issued by NPS which allows for consideration of the potential future threat to ‘natural conditions’ from climate change (Memorandum from Director Jarvis; 06 March 2012 Subject: Applying National Park Service management policies in the context of climate change). This memorandum states that decisions should be based on the best available science, decision-making should be transparent, maintaining natural conditions and eliminating human dominance on landscape remain viable management strategies, and managers are not accountable for impairment due to factors outside of Park boundaries that cannot be controlled, and specifically references climate change. Within park boundaries, managers are directed to continue to utilize “practices targeted to maintain “natural conditions”” even though it is acknowledged that “natural conditons” are increasingly difficult to characterize. When managing to mitigate climate change involves manipulating the landscape to create “unnatural” conditions in a park, some policy conflicts may arise. Nevertheless, managers are not absolved from pursuing “cooperative conservation and civic engagement to mitigate impacts arising from external forces” (e.g. climate change).

Another major legal and policy factor is the National Environmental Policy Act (1969). This Act requires environmental analysis for many federal actions, including social and economic impacts of federal management activities.

Meeting the intent or requirements associated with each of these obligations simultaneously can be difficult without clearly articulated goals, objectives, monitoring strategies, and management direction.

A Way Forward: Structured Decision Making to Inform Resource Management Decisions

Structured decision making (SDM) is a formal, structured process for problem solving that decomposes a problem into interrelated parts and is driven by a focus on values-based objectives (Hammond et al. 1999, Gregory and Long 2009). Specific objectives reflect the concerns and values of the decision maker and any involved stakeholders. The decision maker(s) can represent a single person or entity, or a consortium of parties responsible for implementing a decision. The process is value-focused because it starts with an explicit articulation of objectives. The process also separates the components of the decision so that each can be carefully considered and analyzed. In this way, impediments to decision making in complex scenarios can be identified and resolved. The key elements of a structured decision making process are:

1. Frame the problem (identify the decision to be made, the decision maker, legal and regulatory context, and the essential elements of the decision)
2. Specify the objective(s) and measureable attributes
3. Identify creative management action alternatives, which are focused on satisfying the objectives
4. Identify the probable consequences for each alternative (via qualitative and quantitative predictive models)
5. Analyze the trade-offs
6. Decide on an action(s)
7. Implement chosen action(s) and monitor system response to determine effectiveness of the action or to inform adaptive management in the case of repeated decision-making under uncertainty

Decision making is an iterated process, where the framework for making an initial decision is set up in a structured decision making workshop(s). If management decisions are iterated through time with an opportunity to change decisions based on new information, a process of formal adaptive management may be useful (Williams et al. 2009). The components in the initial decision framing can be revised when new information becomes available, management objectives change, new alternatives are identified, or monitoring reveals that the models used to choose among alternatives do not adequately capture system dynamics.

In January of 2011, a group consisting of SHEN staff, the FWS Ecological Services *Plethodon shenandoah* species lead, US Geological Survey (USGS) decision analysts and ecologists, and University of Virginia climatologists developed a basic SDM decision model. The group articulated the initial problem statement (i.e., How should SHEN respond to the potential climate-change driven increase in extinction risk for the endangered, high-elevation *P. shenandoah*?) and set fundamental objectives of 1) maximizing the likelihood of persistence of the species within its native range, while 2) following NPS policy (while considering that actions needed to meet the salamander persistence objective might conflict with other NPS policies), 3) minimizing costs of any management action that might be taken, and 4) maximizing public acceptance of management. In the process of developing these objectives, decision makers were encouraged to articulate their concerns and consider which objectives were fundamentally important; where fundamental objectives are distinguished from those objectives that are means to achieve a desired outcome. For example, increasing suitable habitat is a means objective, i.e., a means to achieve the fundamental objective of increasing the population persistence of *P. Shenandoah*. The fundamental objectives in this example include ecological (e.g., *P. shenandoah* extinction risk) and agency oriented (e.g., adhere to NPS policy, minimize costs, maximize public acceptance), objectives which must be considered simultaneously.

The group then developed a suite of possible management actions that had some perceived potential to achieve the resource management objectives. This development involved creative "outside the box" thinking as consideration of a wide breadth of technically possible and diverse options is most likely to identify an alternative that will lead to favorable outcomes. The options included actions to manage habitat, such as vegetation manipulation via chemical, mechanical, and natural means; soil and rock manipulation; elimination of direct human activity (i.e., trails); humidity and temperature control (via shade cloths, sprinkler systems, etc); and actions targeted at the species directly, such as assisted relocation (Table 1). Various hypotheses for decline of salamanders motivated development of different types of actions.

Table 1. Management actions, descriptions, and hypothesis addressed by each action. Actions in italics were ultimately deemed infeasible or ineffective by the second workshop participants group and were excluded from further analysis (see *Management alternatives* section below); for those actions that were rejected, the reasons for rejection are included in the definition column.

Action	Definition	Hypothesis
Status quo	Minimize disturbance to salamanders and their habitat in routine park management, research, and visitor activities.	Reduce Human Disturbance
Thinning- tree overstory	Selective mechanical removal of canopy trees (to 50% canopy cover) is expected to create habitat conditions which can be tolerated by *P. shenandoah* but not *P. cinereus*. Application in *P. cinereus* dominated habitat adjacent to *P. shenandoah*-occupied habitats. Treatment locations chosen to increase connectivity among Shenandoah-occupied habitats.	Reduce Interspecific Competition
Thinning- shrub understory	Mechanical cutting of understory woody vegetation. Create habitat conditions which can be tolerated by the Shenandoah salamander but not the red-backed. Application in red-backed dominated habitat adjacent to Shenandoah salamander-occupied habitats. Treatment locations chosen to increase connectivity among Shenandoah-occupied habitats.	Reduce Interspecific Competition

Table 1 (continued). Management actions, descriptions, and hypothesis addressed by each action. Actions in italics were ultimately deemed infeasible or ineffective by the second workshop participants group and were excluded from further analysis (see *Management alternatives* section below); for those actions that were rejected, the reasons for rejection are included in the definition column.

Action	**Definition**	**Hypothesis**
Remove *P. cinereus*	Remove red-backed salamanders from areas surrounding Shenandoah-occupied habitats. Treatment locations chosen to increase connectivity among Shenandoah-occupied habitats.	Reduce Interspecific Competition
Assisted relocation	Assist migration of Shenandoah salamander (aka managed relocation) to areas with future projected suitability under climate predictions.	Adapt to Climate change
Planting	*Portfolio of actions to increase canopy to 80% canopy cover - to increase humidity and decrease temperature. May need to combine with addition of soil and water. Treatment locations chosen to increase connectivity among Shenandoah-occupied habitats.* Reason for rejection: *Vegetation already present where growth is possible and this action is difficult at best and likely infeasible.*	*Adapt to Climate change*
Fire- understory	*Similar to thinning understory, but using fire. Application in red-backed dominated habitat adjacent to Shenandoah salamander-occupied habitats. Choose treatment locations to increase connectivity among Shenandoah-occupied habitats.* Reason for rejection: *Conditions for understory fire rarely occur – likely infeasible.*	*Reduce Interspecific Competition*
Sprinkler	Create more high-humidity habitats for salamanders, likely near Skyland. Would have to be seasonally implemented. Reason for rejection: Logistically difficult if not impossible at larger scales.	Adapt to Climate change
Shadecloth	Install ½ m from ground - decrease ambient temperature and increase humidity. Similar to planting. Reason for rejection: Logistically difficult with extraordinary maintenance costs.	Adapt to Climate change
Clearcut	Removal of all woody veg. We probably wouldn't do this. Application in red-backed controlled habitat adjacent to Shenandoah salamander-occupied habitats. Park would assess physical (i.e. cutting) thinning prior to implementing clear cuts. Reason for rejection: Aesthetically problematic.	Reduce Interspecific Competition
Fire with thinning overstory	Approximate a crown fire. Application in red-backed controlled habitat adjacent to Shenandoah salamander-occupied habitats. Inducing crow fire would require a large area and fire ignition during extreme fire conditions. Reason for rejection: Risks to other resources would be too great to use prescribed fire in this situation.	Reduce Interspecific Competition
Herbicide	Implement on either/both understory and overstory. Similar to mechanical thinning, but with chemicals. Application in red-backed dominated habitat adjacent to Shenandoah salamander-occupied habitats. Reason for rejection: Park would prefer physical (i.e. cutting) thinning.	Reduce Interspecific Competition

Table 1 (continued). Management actions, descriptions, and hypothesis addressed by each action. Actions in italics were ultimately deemed infeasible or ineffective by the second workshop participants group and were excluded from further analysis (see *Management alternatives* section below); for those actions that were rejected, the reasons for rejection are included in the definition column.

Action	Definition	Hypothesis
Trail Closure/relocation	Have done this before for AT. Different resistance depending on whether major or minor trail. Choose locations to increase connectivity among Shenandoah-occupied habitats. Reason for rejection: Extremely difficult from social perspective. Likely small impact.	Reduce Human Disturbance
Remove salamander predators	Trap and relocate salamander predators. Reason for rejection : Likely small effect	Reduce population extinction
Soil augmentation	Add soil to bare talus. Reason for rejection: Extremely difficult if not impossible.	Reduce Interspecific Competition
Add rock/remove soil	Remove substrate from areas of deep soil. Reason for rejection: Extremely difficult if not impossible.	Reduce Interspecific Competition
Enhance natural corridors	Increase connectivity of existing isolated Shenandoah salamander populations by creating corridor habitats with characteristics suitable for Shenandoah salamander occupancy. Reason for rejection: This is not an action on its own. Should be considered for all management actions.	Reduce Interspecific Competition/Adapt to Climate change

The group constructed a variety of conceptual models to evaluate the consequences of each action with respect to the fundamental objective of maximizing Shenandoah salamander persistence under different climate change projections (as determined by climate scientists in the group). When data were not available for development of the models, experts in the group provided estimated values. No formal elicitation method was used, but in the future such methods (e.g., a Delphi process; MacMillan and Marshall, 2006) could be used to capture the uncertainty in the model parameters and avoid psychological pitfalls. The group participants then rated (through expert elicitation) how well each management action met the other objectives in the decision (policy compliance, cost, public acceptance) and ranked the relative importance of the objectives under a variety of biological and management scenarios (e.g., salamander persistence likelihood is high and a proposed action is unlikely to further improve the outcome vs. salamander persistence is unlikely and a proposed action is highly likely to improve the likelihood of persistence). This recognizes a non-linear preference structure, whereby a given change is related to an estimated baseline. Utility relates a decision maker’s preferences to varying conditions. In our case, utility is responsive to the risk attitudes of the decision makers. Preferences therefore relate to the relative probability of each set (or level) of conditions, and may result in a non-linear utility function. This approach incorporates the decision maker’s preferences into considerations of the suite of possible management actions. These preferences are important because a given management action may be most useful for achieving one objective (e.g., reducing extinction risk of the salamander) while being least desirable for another objective (e.g., cost), and are useful for assessing these tradeoffs.

The initial decision analysis during the January 2011 workshop resulted in a “prototype” or preliminary solution to the decision problem. A large benefit of this process was that it clarified and documented the value of considering active management actions – an important outcome given that the climate change and salamander “problem” was perceived by the park to be intractable and thus was inherently subject to inaction. The process also provided insight into key uncertainties that were likely to have a large influence on which management action would be preferred. Identifying these “critical” uncertainties focused data collection for the following field seasons on the uncertainties that were deemed likely to be most relevant to the decision; a formal value of information analysis (e.g., Runge et al 2011) was not conducted. These uncertainties included aspects of species’ distribution, especially whether the species occurs outside its known historic range and a better definition of the lower elevational boundary of the species distribution.

In April of 2012, a second structured decision-making workshop involved additional staff from Shenandoah NP (superintendent, deputy superintendent, and the chief of natural and cultural resources) and staff from the Natural Resource Stewardship and Science Directorate, including the Climate Change Response Program, and the Northeast Regional scientist. Working within NPS policies, in consultation with the ES office of FWS, and considering local public perceptions and considerations, the superintendent of SHEN makes decisions about management actions within the park. The 2012 workgroup reviewed the 2011 team’s initial decision analysis with a particular focus on applying NPS policy to the formulation and weighting of objectives, better defining the policy objective within the context of climate change, and evaluating the feasibility of the alternatives with respect to NPS policy. This group provided an additional range of perspectives to help represent a future superintendent’s perception of the decision (i.e. decision framework). Additionally, representation from multiple levels of the NPS created higher level awareness of potential for controversy from a superintendent’s future decision about the salamander. Finally, some members of the workshop also participate in an NPS Climate Change Policy Working Group, which is critically evaluating policy aspects of NPS response to climate change-induced threats to park resources, and which seeks ‘case study’ examples of those threats to park resource persistence.

Because many participants in the 2012 workshop were not familiar with the salamander or associated research, the workshop included a brief review of the “state of the science,” covering salamander ecology, climate change, and existing models of decision options, and discussing an initial population viability analysis for the salamander. All of these components had high levels of uncertainty that are important to characterize for the decision analysis. The first workshop identified various aspects of the ecology of the species and the expectation of future climate conditions under climate change as two major sources of uncertainty and participants in the second workshop continued to discuss these uncertainties. The presence of uncertainty is not necessarily an impediment to identifying an effective decision. For example, the optimal action might be consistent across a range of uncertainty. Alternatively, a decision maker’s risk attitude can be evaluated to find optimal actions in the face of uncertainty. The process, however, worked explicitly to emphasize uncertainty from the beginning of the decision process in a fashion unfamiliar to some participants. The ecological, climate model prediction, and population viability uncertainties are examined in the following sections.

Ecological Uncertainty

Because the species has not been studied in detail since R. Jaeger’s studies in the 1970-80’s, there exists significant uncertainty in its ecology, including contemporary distribution, habitat relationships, and interspecific interactions. Ongoing research by USGS Amphibian Research and Monitoring Initiative (ARMI) scientists is providing data which will help inform management decisions for this species and resolve important uncertainties that were identified in the initial SDM workshop. At the time of the workshop, unpublished results of research and monitoring for *P. shenandoah* have found:

1. The lower elevation limit exists between approximately 850-900m.
2. There is not strong evidence for local extinction between the 1950-80 period, nor from more recent surveys conducted from 2007-09, due to competition with *P. cinereus*.
3. In contemporary surveys, *P. cinereus* and *P. shenandoah* co-occur less than would be expected by random chance, suggesting some competition or differential selection of habitat does occur
4. The present-day potential distribution is limited to approximately 1km^2 of high-elevation habitat, with approximately 30% of that area occupied by *P. shenandoah*.
5. Habitat preferences for the Shenandoah salamander, as suggested by a site-occupancy analysis of contemporary survey data, indicate that probability of occupancy:
    a. is higher at sites with northern hardwood vegetation communities, including those with basswood and striped maple, and lower at sites where red oak and chestnut oak dominate the landscape;
    b. increases as percent cover of moss and slope angle increases;
    c. increases on certain soil types (e.g., Catoctin-Rock outcrop complex and Myersville-Catoctin complex);
    d. increases with increasing soil depth and
    e. decreases with increasing leaf litter depth and percent cover of soil and leaf litter.
6. From the period 2008-11, for *P. shenandoah*, local (i.e. site level) annual extinction is estimated ~30% and local annual colonization ~2%; for *P. cinereus*, local annual extinction rates are also ~30%, but annual colonization rates are substantially higher at ~20%. These data suggest that, currently, the *P. shenandoah* population is in decline, and *P. cinereus* may be more likely to colonize in areas with local extinctions of *P. shenandoah*. There is some evidence that extinction rates are higher, and colonization rates lower, for *P. shenandoah* in the presence of *P. cinereus*.

Climate Model Prediction Uncertainty

Both temperature and humidity are expected to change in the Mid-Atlantic region in the next few decades, but the uncertainty between global climate models is large (Polsky et al., 2000). Global climate models generally predict warmer and wetter conditions in the Mid-Atlantic region with an increase in average temperature ranging from 1 to 5° C over the next 10 to 100 years (Hawkins et al. 2011). There is considerable uncertainty in downscaling global climate models to areas in complex mountainous terrain and, as a result, model projections need to be refined for Shenandoah National Park. This refinement work is ongoing by climate scientists Stephan DeWekker and Temple Lee (University of Virginia), who participated in the first workshop. For the current decision analysis purposes, we use rough estimates from Regional Climate Models provided by De Wekker and Lee that predict 0.9° C of warming by 2071 (as derived from the Coupled Global Climate Model (CGCM3). De Wekker and Lee, during the first workshop, indicated that most models do suggest an increase in temperatures in the mid-Atlantic region but that models were not consistent for predictions of precipitation. We therefore used three models to obtain a range of temperature and precipitation scenarios: baseline with no climate change, “warmer and wetter”, and “warmer and drier”. Though we did not define specifically what a “wetter” or “drier” environment would be in regards to precipitation, we estimated the effect of increasing or decreasing the percentage of moss cover (a proxy for changes in relative humidity) by + or - 5% at a site on salamander occupancy, and used the corresponding changes in the vital rates in our simulations. We used the estimated effect of increased temperature (based on field observations) on occupancy rates.

Population Viability Analysis

The following results are based on a preliminary modeling approach; future outcomes represent projections based on current information and understanding and as information and understanding change over time, the future projections also may change. While the following analysis is preliminary and should not be used to make final determinations of the extinction risk of the Shenandoah salamander, it allowed the workshop participants to continue to frame the decision.

We conducted a population viability analysis to assess the future probability of the species’ extinction from all suitable local sites using local extinction and colonization rates estimated from observation data. We investigated the effects of various climate and management scenarios on the probability of persistence for 60 years. We used a Markov chain model (Caswell 2001) with local extinction and colonization probabilities estimated from field data. Both extinction and colonization probabilities were allowed to vary stochastically in our simulations, with values drawn from a beta distribution bounded between 0 and 1 (Evans et al. 2000). The model was initialized with 172 occupied sites to correspond to the presumed range of the Shenandoah salamander. Here, a site is a 100*100m grid cell, and is interpreted as a local population. The initial occupancies of the Shenandoah salamander, the red-backed salamander, and both species together were set to the mean estimates from two-species conditional occupancy models (Richmond et al. 2010). We ran 5000 simulations for each scenario.

To understand how uncertainty may influence the management decision, we utilized several different model scenarios constrained to two main uncertainty components of the decision problem:

uncertainty in future ecosystem state due to climate change and uncertainty in ecological interactions between *P. shenandoah* and its potential competitor, *P. cinereus*. We included three climate change scenarios (1) no climate change, (2) warmer and wetter (resulting from more precipitation), and (3) warmer and drier (resulting from less precipitation). Current climate change models do not anticipate cooling in these high-elevation habitats (De Wekker personal comm.). Similarly, due to ecological uncertainty about the species, we tested no competition (both species have colonization and local extinction rates which are independent on the presence of the other species) and competition (colonization and local extinction rates are influenced by the presence of the other species) scenarios (Table 2). The influence of each species on the colonization or extinction rates of the other was calculated as the ratio of sites occupied by each species alone to the proportion of sites occupied by both species, estimated from the field data using the two-species conditional occupancy model. For each simulation run, we recorded the number of occupied sites that went extinct and the number of years to extinction of all sites in the metapopulation, and the mean probability of extinction for each competition+climate change scenario.

The simulation under the no climate change scenario revealed that, while the Shenandoah salamander population persisted for 60 years, it ended the simulation with a low average proportion of occupied sites. The results between models with or without competition varied little without climate change, suggesting that competition did not strongly influence the projected extinction risk. In contrast, significantly more pronounced differences in extinction risk (Fig. 1) are seen among the different climate change scenarios with mean extinction probabilities between 25 and 36% under warmer climate scenarios; median extinction times under both climate change scenarios occurred around 50 years. Competition may exacerbate extinction risk in a warmer and drier future.

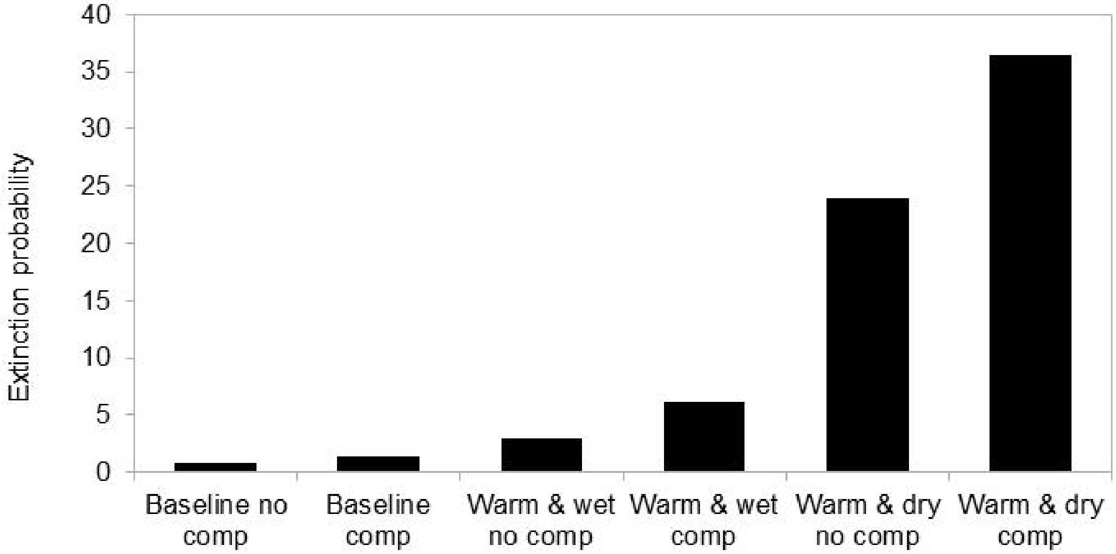

Figure 1. Extinction probabilities after 60 years for the Shenandoah salamander for various model scenarios. Baseline = no climate change, warm & wet = warming and wet climate change scenario, warm & dry = warming and dry climate change scenario, no comp = no effect of each species on the occupancy of the other, comp = each species affects the local colonization probability of the other species.

The analysis also suggested that climate change may have a larger effect on our expectation of extinction risk than competition (Table 2). Competition does exacerbate extinction risk (especially under the warm and dry climate future), but the effect is estimated to be smaller, on average, than the potential climate change impact.

Table 2. Maximum mean 60-yr extinction risk for the Shenandoah salamander, given current hypotheses of how climate change and competition with the red-backed salamander affect occupancy of the species.

	Competition		
Climate Change		Yes	No
	Yes	36%	24%
	No	0.3%	0.2%

By simulating the likelihood of extinction under a variety of scenarios, this population viability analysis allowed the workgroup to better evaluate the need for action. Workshop participants were provided Table 2 and informed that initial modeling of the population resulted in an understanding that competition did not have as large and influence on extinction risk, while extinction risk increased when climate change was incorporated.

Decision Structure: Results from the 2012 Workshop

Management Objectives

After framing the problem, the next step in our decision analysis was to specify clear and concise objectives. Participants in the first workshop identified four objectives which were of fundamental importance to the Superintendent of Shenandoah National Park (who was identified as the decision maker). The 2012 group retained the four fundamental objectives and draft measurable attributes from the 2011 workshop; all participants agreed that the objectives were appropriately stated and complete. The four objectives were:

1. Maximize the probability of *P. shenandoah* persistence.
    a. The probability of persistence of the Shenandoah salamander under various circumstances was based on our population viability modeling results.
2. Adhere to National Park Service policy. This objective is comprised of multiple sub-objectives (as noted below). Measurable attributes for each sub-objective were represented on a constructed scale from 1-5 (1 representing the worst case and 5, the best case), indicating relative consistency with park policy; each sub-objective was deemed equally important to achieving the objective.
    a. Minimize human influence and management on natural processes
    b. Allow for use and enjoyment of park resources by visitors
    c. Minimize negative impact on other native species in the park, which is analogous to conserving the high-elevation ecosystem in which the salamander resides.
3. Maximize public acceptance of salamander management.
    a. The measurable attribute was represented on a constructed 5-point scale
4. Minimize cost.
    a. The measurable attribute was represented on a real scale (dollars), assuming an optimal level of implementation.

Management Alternatives

Following the discussion of management objectives, the group then reviewed the list of potential management actions that were articulated in the 2011 workshop (Table 1). Again, these management actions were determined to be activities the Park could potentially implement that might help prevent extinction of the species from its native habitat (i.e., Shenandoah National Park). The group assessed each action for feasibility, with the goal of reducing the list of potential actions to simplify the decision analysis and examination of tradeoffs of each action. This resulted in removal of alternatives that were likely irrelevant or expected to have small effects on persistence of the salamander in the system (“trail closure or relocation’, ‘predators’); or were deemed difficult due to causing large impacts on public use (“trail closure or relocation”), having extraordinary costs (‘planting’, ‘shadecloth’, ‘sprinkler’, soil/rock augmentation and removal), being physically infeasible at small spatial scales (‘fire alternatives’); or were deemed included in other actions (‘clear cut’, ‘herbicide’, ‘corridors’, ‘change in routine park management’). The group retained 5 alternatives: Status quo; Thinning- overstory; Thinning- understory; Remove *P. cinereus*; and Assisted relocation. The group expressed strong initial preference for the ‘Status quo’ alterative as the group did not feel that sufficient evidence was available to warrant more active management for the species (as based on the “state of the science” review from earlier in the workshop), this action does not result in manipulative management of the Shenandoah salamander, and was viewed to be the least intrusive on high elevation park resources and public perception, and inherently required no increase in costs. Status quo bias is acknowledged as a ‘psychological trap’ in decision making (Samuelson and Zeckhauser 1998).

Decision Analysis

Our decision analysis evaluated the projected effect of the five retained management actions on all four fundamental objectives. To perform the analysis, we used a common analytical approach called Simple Multi-attribute Rating Technique or SMART (Hammond et al. 1999, Goodwin and Wright 2004). In the analysis, a consequence table is used to display the performance of actions on each objective (i.e., how well each action meets each objective). Analysis of the tradeoffs amongst objectives, to identify the optimal decision, is based on a normalized performance score for each management action with respect to the fundamental objectives, weighted to account for the relative importance of each objective as determined by the decision maker (see e.g., Converse et al. 2013). Uncertainty in predicted performance of each management action can be incorporated into the analysis via sensitivity analysis.

Weighting the Objectives

A primary reason for convening the 2012 workshop was to elicit the range of objective weights on each objective from various perspectives within NPS. Objectives are weighted because some objectives are more important than others and should thus be more heavily considered (i.e. weighted) when determining the best decision. Each participant chose the objective that was most important to him or her, assigned that objective a weight = 1, and then assigned weights to the remaining objectives relative to the ‘most important’ objective (the ‘Global scales’ approach). For example, as noted in Table 3, the first workshop members determined that persistence of the salamander was the most important objective (score = 1) while cost was only 20% as important as salamander persistence (score = 0.2). When the first workshop assigned weights across all objectives, the normalized weight on the salamander objective was 0.43, indicating that 43% of the “importance” of the decision should be associated with meeting the salamander objective. In contrast, if all objectives were deemed equal, the salamander persistence objective would have received a normalized weight of 0.25. The second workshop participants differed somewhat in the distribution of weights, but all gave the salamander objective higher weight than if all objectives were equally weighted (Table 3).

SMART Analysis

The example consequence table in Appendix 1 was developed by comparing all objectives against the five management alternatives. Values for the salamander objective were informed from habitat-based occupancy models and the results from the PVA. Values for the other objectives were developed by asking participants to assign values (depending on the measurable attributes) describing how each management alternative would affect each objective. For example, participants estimated that if the management action to remove red-backed salamanders were chosen, the public acceptance would be low, so participants assigned the outcome for this objective a value of 1 (on a scale of 1-5, with 5 being the ‘best’ outcome). On the other hand, they gave the ‘allow for public use and enjoyment’ part of the ‘Adhere to National Park Service policy’ objective a value of 5 on that scale, as they concluded the ‘removing red-backed salamanders’ alternative would have little effect on the ability for visitors to enjoy park resources (e.g., hiking on trails, seeing intact forest canopy).

Table 3. Weights on each of the four objectives, elicited from the six NPS participants in the second workshop, and the resulting normalized weight on the salamander objective. Participants are specified by their roles in this decision. The 'proxy' decision makers are resource managers, and the decision maker is the park superintendent; three participants provided guidance on NPS policy from both regional and national perspectives. For comparison, the normalized weights used in the first workshop, as well as equal weights are included. Average weights for workshop 2 participants were calculated by first normalizing the scores and then averaging across all participants. While four of six participants ranked the 'NPS Policy' objective highest, they indicated it was in part due to an interpretation that NPS policy encompasses other objectives; the 'Salamander' objective was ranked next highest in these cases.

	Objectives				**Resulting weight on salamander objective**
	Salamander	**NPS policy**	**Public**	**Cost**	
Decision maker (proxy)	0.8	1	0.3	0.5	0.31
Decision maker (proxy)	0.9	1	0.6	0.5	0.30
Decision maker	0.9	1	0.7	0.3	0.31
Regional policy	1	0.7	0.4	0.6	0.37
National policy	0.7	1	0.5	0.5	0.26
National policy	0.9	0.7	0.8	1	0.26

Comparison of two workshop results to equal weights

1st workshop	0.43	0.39	0.09	0.09
2nd workshop (avg)	0.30	0.31	0.19	0.20
Equal	.25	.25	.25	.25

Sensitivity Analysis

We elicited multiple consequence tables from participants under all combinations of scenarios of climate change and interspecific competition. Using these four tables, we performed a sensitivity analysis to demonstrate the importance to the decision of the weight allocated to maximizing the persistence of the Shenandoah salamander, and of the influence of our uncertainty under divergent climate change model predictions. We combined the 4 consequence tables into a single table of the expected (mean) value for each combination of alternative and objective. We fixed the probability of competition limiting the distribution of *P. shenandoah* = 0.5, and for a given probability of climate change (evaluated from 0-1 in increments of 0.2), we then calculated the scores for each alternative by assigning weights to the salamander persistence objective (Fig. 2). The relative weights of the remaining three objectives remained constant while their absolute weights varied according to the weight assigned to the Shenandoah salamander persistence objective.

Because of the initial preference for the 'status quo' alternative, and to contrast the active management alternatives with that alternative, we identified the point at which the optimal decision switches from 'status quo' management to the 'assisted relocation' alternative, which had the highest score under the SMART analysis (Appendix 1). Using the weighted average outcome for each objective under each management alternative (i.e., the expected value across the 4 consequence tables), we identified this point by using one of our hypotheses - that warming and drying in high elevation habitats due to climate change will result in conditions which are intolerable for the Shenandoah salamander (i.e., 'bad' climate change) - to investigate how reducing uncertainty in the probability of this ‘bad’ climate change occurring affects a decision for active management (‘assisted relocation’) versus no active management (‘status quo’).

As the probability that ‘bad’ climate change will occur was increased, the analysis indicated that ‘assisted relocation’ would become a better decision and the relative weight assigned to the salamander objective at which the optimal decision switches from ‘status quo’ to ‘assisted relocation’ would decrease (Fig. 2). For example, if we are certain that ‘bad’ climate change will not occur [e.g., Pr(Bad CC) = 0], we find that changing the weight for salamander persistence [meaning, assessing the range in the response from assuming we care very little about salamander persistence (weight =0) to determining that salamander persistence is our most important objective (weight = 1)] does not lead to a switch in the decision from ‘status quo’ to ‘assisted relocation’ (i.e., the lines do not cross, and therefore the decision is insensitive to the relative weight on the salamander objective). In contrast, we find that, as the modeled probability of climate change increases [e.g., Pr(Bad CC) > 0.6], the relative weight on the salamander objective at which the decision switches from ‘status quo’ to ’assisted relocation’ decreases to <0.5 (Fig. 2).

As noted in the objective weighting discussion above, the mean weight for the salamander provided by the second workshop group was 0.3. Using that weight, the results (Fig. 2) suggested that ‘active relocation’ will become the preferred decision when confidence that climate change will negatively impact the salamander approaches 80%.

Prediction Uncertainty

One benefit structured decision making provides to decision making is the ability to consider each identified component of uncertainty in the analysis (Nichols et al. 2011). In the case of the Shenandoah salamander, where climate change is a new threat not originally identified in the species’ recovery plan, climate change still can be evaluated alongside other sources of uncertainty. To determine decision-maker perceptions of uncertainty regarding the salamander, participants were asked to identify sources of uncertainty they found likely, to elicit the relative importance of these sources to the perceived ability to make a decision, and to identify where in making a decision they viewed consideration of uncertainty to be most meaningful (Table 4). Participants struggled with the level and diversity of uncertainty in this decision problem, and stressed that, in order to make a decision for large-scale (e.g., range-wide) management, these uncertainties would need to be substantially reduced. Participants concluded that one means to address this uncertainty would be to have the scientific evidence associated with the decision be evaluated by an independent scientific panel convened by NPS, which is typical of the agency before implementing larger or more controversial natural resource management actions. Notwithstanding these uncertainties, our analyses indicated that active management should remain a highly viable alternative whenever salamander persistence and mitigating population decline are accepted to be important objectives.

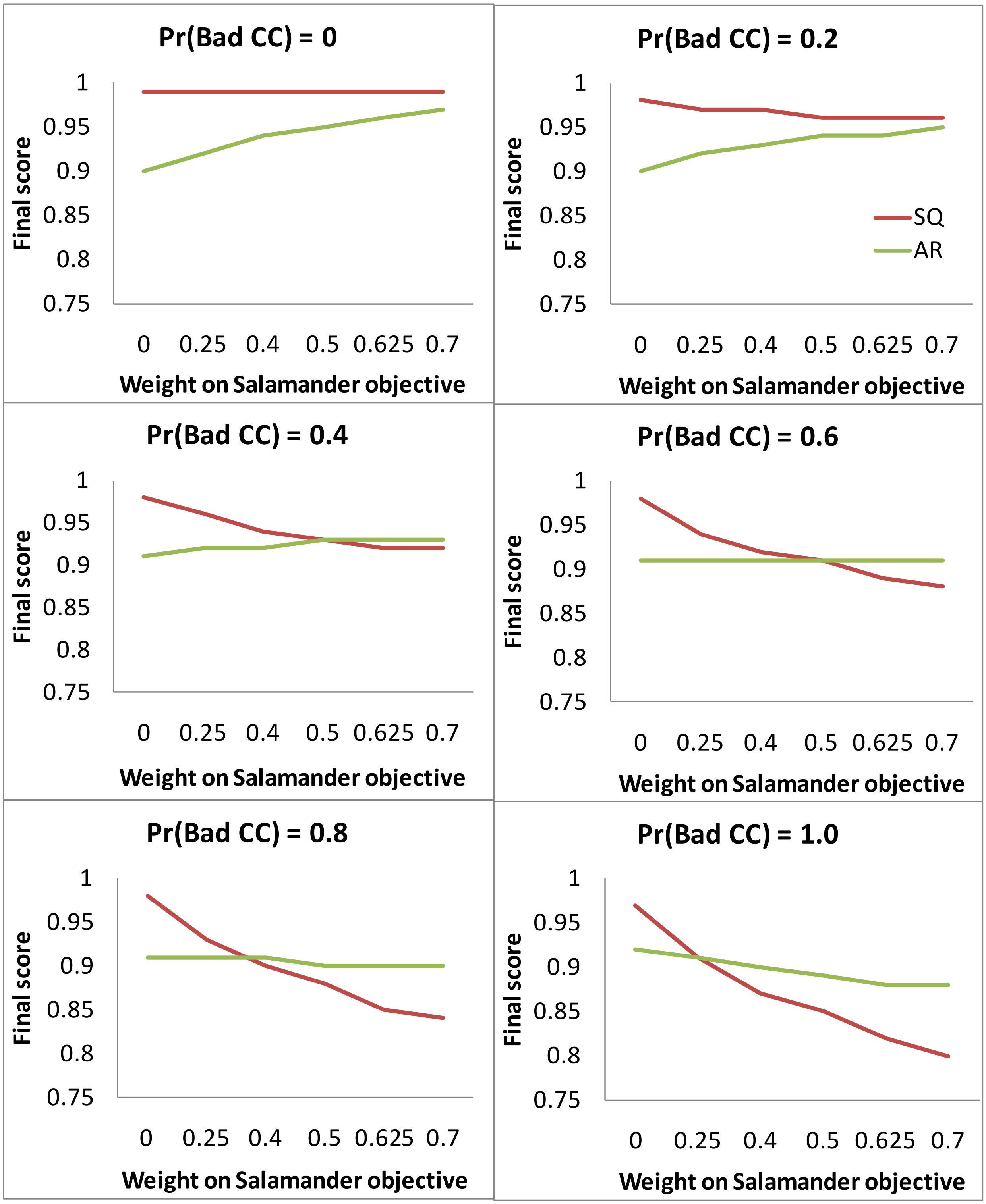

Figure 2. Sensitivity analysis of the decision to both changing the relative weight on the salamander objective ('Maximize the likelihood of *P. shenandoah* persistence') and changing our belief that climate change will negatively influence salamander populations [Pr(Bad CC)]. The red line represents the score from the multi-attribute consequences table (Appendix I) for the 'status quo' (SQ) management alternative and the green line represents the score for the 'assisted relocation' (AR) alternative. The y-axis is the weighted summed (over all alternatives) score for that alternative.

Table 4. Knowledge uncertainty and value rankings by topic. The entries in the ‘Confidence’ and ‘Value to management’ columns were elicited as Low/Medium/High; of particular interest are uncertainties with low perceived confidence and high perceived management value. Confidence estimates were elicited from the biological experts; value to management judgments was elicited from the second workshop group.

	Confidence in knowledge	**Value of knowledge to management**
Climate change uncertainty		**H**
High-elevation salamanders will respond to climate-induced habitat changes	L/M	H
Temperature has higher effect than humidity	M	H
Species-specific effects of change in temperature/humidity on population	L	H
Some increase in temperature tolerable (ecological threshold question)	L	H
Further increase in temperature has negative effect	L	H
Red-backed could be more tolerant but still sensitive	L	M
Ecological uncertainty		
Competition		**M**
Red-backed salamander has expanded its range over geologic time	H	L
Red-backed competing with Shenandoah limits current Shenandoah distribution	M	M
Direct competition contributes to local Shenandoah extinction (displacement or mortality)	L	M
No overlap in distribution <900m	H	L
Zone of competition exists >900m	M	L
Characterize environment at 900m transition zone	M	M
Mechanism of competition 1) red-backed has higher clutch size	L	L
Mechanism of competition 2) red-backed has greater access to surface	L	L
Mechanism of competition 3) red-backed has higher colonization rate	H	L
P. shenandoah distribution and abundance		**M-H**
Historic range ~6km^2	H	L
Lower elevation limit 900m	H	L
Population is in decline (2008-present)	M	H
Current rates: 40% occupancy	M	H
Current rates: 70% persistence	M	H
Current rates: low colonization (2%)	M	H
No decline (1950-2008)	L	L
Current occupancy related to known habitat variables (temp and humidity, vegetation cover)	M	H

Discussion

Shenandoah National Park initiated this SDM process to inform its determination of what, if any, action it should take to ensure persistence of the Shenandoah salamander, given the potential impacts of climate change. If a decision to actively manage for the species was not indicated immediately but was determined to be likely in future, of perceived importance was determining what information would be needed to allow a future decision. Managers ultimately wanted to evaluate the appropriateness of no direct management action for the Shenandoah salamander (i.e., the status quo).

This decision analysis indicated that "assisted relocation" may be an appropriate management action among the few actions considered for improving the likelihood of species persistence, given the specified objectives and estimates of management and climate change effects on the Shenandoah salamander, which are likely to change with additional information and improvements to this initial modeling effort. The analysis clarified the need for more information prior to developing an active management program and suggested that focusing planning now on some future efforts in that direction might be prudent. The SDM workshop also revealed the importance to NPS staff of confronting conservative management principles for managing endangered species even under high levels of uncertainty and when extinction is estimated to be of moderate likelihood.

The notion of 'urgency to act' was discussed at multiple times during this workshop; participants indicated that their feeling of urgency to implement near term, large-scale management actions was conditional on the demonstration of a large and near certain risk of imminent extinction. This is differentiated from small-scale experimental actions designed to learn whether the proposed alternatives would be detrimental or beneficial to the salamander and the rest of the high-elevation ecosystem, which would be allowable. This hesitancy to act was due to a high level of certainty that large scale actions would harm some objectives (e.g. "natural" processes) with a low level of certainty that it would benefit others (i.e. salamander persistence). An initial population viability analysis using model results and expert opinion on future climate conditions from the first workshop, indicated that, over the next 60 years, the probability for species extinction increases from approximately 0% to 35%, when comparing "no detrimental climate change" vs. "warmer and drier climate change" scenarios, (Table 2), using current but imperfect knowledge of the salamander and climate change. Despite the fact that a federally-endangered species was involved, most participants in the second workshop did not consider this projected change to reflect an urgent problem that would require immediate and large scale or costly actions, given all the recognized uncertainties.

Based on the perceived lack of short term urgency, the NPS participants in the second workshop indicated that they would not currently advocate large-scale active management until three conditions were satisfied: (1) a high level of scientific agreement on the urgency to implement active management, (2) a clear understanding of the specifics of the threat to the population or habitat, and (3) a high degree of confidence in our ability to predict the results of a management action. The group suggested that a scientific consensus should be documented by more than peer-reviewed literature and specifically recommended the creation of an external scientific review group to evaluate the state of the science on the issue and to review the assumptions and results from this SDM workshop and related current research and monitoring projects.

Because any management actions taken under the assumption that climate change is the primary threat to the salamander could be maladaptive if other stressors are instead more important to a population decline (and are exacerbated by management in response to climate), the participants indicated that climate change should be implicated as the primary threat to the species prior to an action being taken, and that the burden of proof was to establish the existence of a climate change threat within the context of other existing stressors - not to prove the lack of existence of this threat. The participants acknowledged that there were few NPS examples of active management actions taken to support species persistence under climate-induced threats, and that, therefore, these types of proposed actions are perceived as more “experimental” than common practice and may receive a higher level of scrutiny due to political or societal pressure. Successfully responding to this scrutiny and achieving agreement for active manipulation of park resources to mitigate climate threats may require more substantial certainty of cause and certainty of success than actions targeting more “traditional” threats. Though climate change is considered in the decision analysis as an additional (but not distinctly different) source of uncertainty (Nichols et al. 2011), throughout the discussion it was apparent that participants considered climate change uncertainty differently than other uncertainties in this decision problem (e.g., ecology of the Shenandoah salamander). Participants discussed the necessity to directly link management actions with human-induced risks; such that the factor that is managed must correspond to the risk (e.g., closing trails where use or presence of trails is demonstrated to increase extinction risk). As one participant remarked, “heroic measures [to rescue or maintain the species] are not supported unless human activities are demonstrated to cause an increased extinction risk.” With respect to the Shenandoah salamander, participants clearly desired greater certainty in (1) extinction risk, (2) definitive causes of extinction probabilities (particularly with respect to competition and climate change) and (3) probable response of the species to the proposed management alternatives.

The workgroup spent much time trying to characterize the appropriate timeframe for considering the decision. For example, as noted above, climate models and the population viability model were designed for a 60 year timeframe but not for determining what is the appropriate timeframe for characterizing extinction risk from a NPS policy perspective or for establishing what is the appropriate planning horizon for conceptualizing the decision within the NPS mission of preserving resources unimpaired “for future generations”. One participant in the workshop expressed that “long-term” conservation should mean that their “children’s children” would have an opportunity to experience resources as we currently enjoy them. This concept implies that a three-generation or 100-year model might be most appropriate for assessing this decision.

Of important note, NPS participants expressed caution regarding active management actions when operating within the context of climate change – an environmental threat that may require reinterpretation of historic NPS policy positions. Regardless of any climate change threat, the group noted that because habitat manipulation can easily be maladaptive, the Endangered Species Act and NPS policy call for thorough and careful consideration before taking action. Recurring points of discussion in the workshop focused on gaps in information (i.e., uncertainty) and the degree of urgency for the need to act. The current decision model helped inform the time frame of this urgency and also suggested that reducing uncertainty related to climate change was more important to the decision than reducing uncertainty about certain aspects of the species biology (e.g., competition effects). It was clear from their discussion that the group was not comfortable with the high levels of uncertainty in many aspects of the decision framework regardless of how this uncertainty was captured or represented in the decision analysis; this strongly suggests the need for inclusion of non-neutral risk attitudes in the next stage of the decision analysis. It is possible that this discomfort cannot be alleviated because some levels of uncertainty in the decision framework cannot be reduced with reasonable effort, particularly many of those that were perceived to be most important by the work group (e.g. climate change impacts; see Maslin and Austin, 2012). To better address this discomfort, it may be important to determine the relevant thresholds for certainty needed to take action, meaning, under what context (i.e. system state) would manipulative actions be acceptable? If it is unlikely that those certainty thresholds can be met with reasonable effort, a decision to implement a manipulative action would be equally unlikely. As a result, further research into what manipulative action would be most appropriate (i.e. via an adaptive management plan) would not be an efficient use of funds.

Through the SDM process, we identified the various sources of uncertainty, participant’s perceptions of how uncertainty affects their ability to make an informed decision, and model-based assessment of the contribution of uncertainty to choosing among alternatives. Reducing uncertainty in decision making is a principle objective in a monitoring program (Nichols and Williams 2006), and identification of explicit management objectives is an important first step in bridging the ‘research-implementation gap’ (Lauber et al. 2011). USGS and UVA scientists are currently collecting new data in the park that may further elucidate the projected climate effects on population viability projections (thus affecting perception about the urgency for action), triggering a need to revisit the decision analysis as new information becomes available.

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Appendix A. Results from simple multi-attribute rating technique.

Consequence table relating the 5 management alternatives (from Table 1) with the 4 fundamental objectives, their measurable units and target goals. The second objective has 3 sub-objectives. Here we report the results under the expected (mean) values across all climate and competition scenarios (evaluated with probabilities of warm and dry climate change and competition = 0.5). Scores were normalized and then combined using weights assigned to each objective (here we present the average normalized weights from workshop participants; the 'Adhere to park policy' objective was assigned a single weight, and for this table we divide this weight evenly across the sub-objectives) The sum of the weighted scores is used to evaluate the optimal management alternative with respect to the objectives, given the combination of weights, and expected effect of each alternative on each objective. The table demonstrates that the 'Status quo' alternative received the highest final score, followed by 'Assisted relocation.

NORMALIZED SCORES				**Management Alternatives**				
Objectives	**Units**	**Goal**	**Weights**	**Status quo**	**Red-backed removal**	**Assisted relocation**	**Overstory**	**Understory**
1. *P. shenandoah* persistence	Pr(persistence) over 60 yr	Max	0.30	0.861	0.879	0.929	0.674	0.824
2. Adhere to Park policy			0.31					
Min influence	5 pt scale (1 = worst, 5 = best)	Max	*0.10*	0.813	0.375	0.750	0.188	0.375
Public use	5 pt scale (1 = worst, 5 = best)	Max	*0.10*	1.000	1.000	1.000	0.750	1.000
Natural/cultural resources	5 pt scale (1 = worst, 5 = best)	Max	*0.10*	1.000	0.500	0.750	0.375	0.688
3. Public acceptance	5 pt scale (1 = worst, 5 = best)	Max	0.19	1.000	0.313	1.000	0.438	0.688
4. Cost	dollars ($K) annualized over 5 yr	Min	0.20	1.000	0.857	0.857	0.886	0.914
Sum of weighted scores (for each alternative)				0.94	0.69	0.90	0.60	0.77

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National Park Service
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Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov