Management and monitoring of an endangered high-elevation salamander under future climate change.

A Case Study from the Structured Decision Making Workshop
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Decision Problem

In many national parks, high-elevation biota are severely threatened by climate change. 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 (including a no action alternative) that might mitigate the potential negative effects of climate change. Our ultimate goal is to develop an iterative state-based decision process, updated with information from a monitoring program designed to inform decision makers on the distribution of *Plethodon shenandoah*. In this workshop, we simplified the decision to a one-time event over a 30-year period to develop a rapid prototype, which can be tested, revised, and built upon. In addition to local benefits, this project could also provide a template for assessing climate change impacts and mitigating management actions on other high elevation biota, such as the federally threatened Cheat Mountain salamander, or the rare Weller's and Peaks of Otter salamanders.

Resource managers at Shenandoah National Park (SHEN) need to develop a management plan and evaluate ongoing management actions with respect to *P. shenandoah*, which anticipates the effects of climate change on the species, includes a desire to limit active management, and is sensitive to other aspects of the high-elevation ecosystem.

Background

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 on federal actions that may affect those species. The National Park Service Organic Act (1916) obligates the preservation 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. In addition, the National Environmental Policy Act (1969) requires environmental

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assessments 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, and management direction.

Ecological context

The federally endangered salamander *P. shenandoah* is found nowhere else on earth except within the boundaries of Shenandoah National Park, and its entire potential range consists of approximately 6 square kilometers of high elevation (>800m) 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 is believed to have expanded 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 can be further subdivided into a categorical variable, 'talus type,' which integrates vegetation cover, soil depth and exposed rock cover, and captures variation in temperature and humidity gradients. Talus type is presumed to be a proximate variable for temperature and humidity, to which a salamander may ultimately be responding, and has been used to describe the realized niche of *P. shenandoah* (Jaeger 1971_b).

Both temperature and humidity are expected to change in the Mid-Atlantic 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 these projections need to be refined for the Shenandoah National Park.

Decision Structure

We applied a formal, structured process for decision making, which is comprised of 5 interrelated parts, is addressed in succession, 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 stakeholders, which can represent a single person or entity, or a consortium of parties responsible for implementing a decision. The process is value-driven because it starts with an explicit articulation of objectives. The process also decomposes 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 resolved. The components of a structured decision making process are:

1. Frame the problem (identify the trigger, 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 affecting the objectives

4. Identify the consequences for each alternative (via qualitative and quantitative predictive models)
5. Analyze the trade-offs
6. Decide on an action(s)

Structured decision making is an iterative process, and the components can be revised iteratively so that a satisfactory decision can be made. An approach that has been found to be useful is to start with a prototype decision, which is a simpler decision that might not include all possible details. The idea of a rapid prototype arises from engineering; a rapid prototype can be created and used for testing solutions without the cost of a full-scale version. A prototype can be more readily revised and provides a basis that can be developed more fully later on . It is often the case that the prototype serves well as a nearly full-scale solution. During the workshop, we created a 'rapid prototype' of the decision by completing two iterations of the 5-part process above.

Objectives

After framing the problem, the next step in decision analysis is to specify clear and concise objectives. During this part of the process, decision makers are encouraged to articulate their concerns and consider which objectives are fundamentally important; fundamental objectives are distinguished from those objectives that are means to achieve a desired objective. For example, increasing suitable talus type habitat is a means to increase the population persistence of *P. Shenandoah*, which is the fundamental objective. The fundamental objectives include ecological (e.g., *P. shenandoah* occupancy/persistence) and agency mission oriented (e.g., adhere to park policy) objectives, which must be considered simultaneously. These fundamental objectives should be refined in the future development of the decision framework. For the rapid prototype, we considered four fundamental objectives with draft measurable attributes:

1) Maximize *P. shenandoah* persistence.
    a. We presumed that occupancy is related to the probability of species persistence within the known historic range. We built a relationship between occupancy and species persistence by eliciting expectations of persistence for a variety of occupancy values from participants (Figure 1). Thus, occupancy was considered to be a proxy measure of persistence. Population viability analyses or other population modeling will be undertaken to further understand the relationship of occupancy to population sizes and persistence, and to identify an optimal population target.
    b. The target was preliminarily set to the species occupancy (within its known distribution) estimated during 2007-09, because there has been no apparent reduction in the species' range since it was listed in 1997 to the present.
2) Adhere to park policy. This objective is comprised of multiple subobjectives (as noted below). Measurable attributes were represented on a constructed scale from 1-5, indicating relative consistency with park policy.
    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 talus ecosystem.
3) Maximize public acceptance of salamander habitat management.

   a. The measurable attribute was represented on a constructed 5-point scale proportional to the number of calls we expected to receive objecting to the action, assuming public knowledge of the action.

4) Minimize cost.
   a. The measurable attribute was cost per acre over 30 years, assuming an optimal level of implementation .

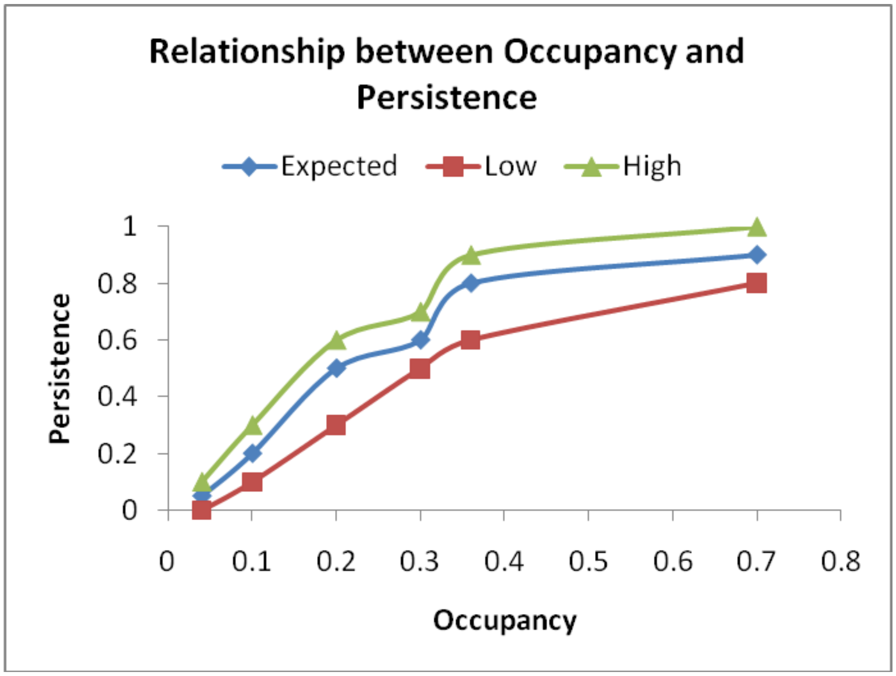


Figure 1. Elicited relationship between *P. shenandoah* occupancy and probability of persistence. The group provided the expected, low, and high range of the relationship. Given this curve, for any occupancy rate (*x*), we can calculate the probability of persistence (*y*). Finding the intercepts and slopes of the two lines (y = mx + b), allowed us to convert each occupancy rate (x) into the appropriate persistence rate (y). We use these slopes and intercepts in the Consequence Tables. (These relationships were used in the prototype and will be revised based on subsequent population viability analyses.)

Alternative actions

After specifying the objectives and measurable attributes, management actions are considered, which could affect the fundamental objectives. Management actions should include a full suite of potential interventions, including actions “outside the box.” A wide range of individual management actions were identified, and then grouped into 6 portfolios that represent a range of management alternatives related to our hypotheses of system-limiting factors (Table 1). We recognized that the variety of management actions within a single portfolio would not be suitable for every location within the *P. shenandoah* range, but in this spatially implicit approach, we assumed that the most suitable management action from within a given portfolio would be implemented. We considered a 30-year planning horizon for the successful application of the management portfolio, to facilitate consideration with the climate change models. We also recognize there is significant uncertainty in the ecology of *P. shenandoah*, and its relationship with *P. cinereus* (assumed to be its chief competitor; Jaeger 1970, 1971$_a$, 1980). Data collected in the future will be used to reduce this uncertainty, allowing better predictions of the relationship between the management portfolio and the expected response. Recall that 'talus type' represents a combination of habitat characteristics which has been used to describe the limits of the distribution of *P. shenandoah* (Jaeger 1970), and we continue its use for simplicity. Talus type I contains rock with some lichen cover, with no soil or vegetation. Talus type II includes no soil under rocks, but organic material is located between rock crevices. Herbaceous cover exists and there are few trees, and they have broad canopies. Talus type III has abundant soil and vegetation and is always surrounded by Type I or II talus and is similar ecologically to the soil environment. Talus type IV is comprised of soil micro-habitat , with few emerging rocks.

Table 1. Alternative management actions, grouped into portfolios (P1-6).

P1-Reduce competition via microclimate (warmer/drier)	**P2-Expand range via assisted colonization**	**P3-Reduce competition directly**	**P4-Status quo**	**P5-Eliminate direct human influence**	**P6-Expand range via microclimate (cooler/more humid)**
Remove soil (Talus type IV)	Translocate *P shenandoah* to other suitable habitat within the historic range	Remove *P. cinereus* from areas of co-occurrence	Maintain current activities	Further restrict access	Soil augmentation (Talus I)
Prescribed fire (Talus III/IV)	Establish corridors within the historic range to allow natural colonization			Modify park mgmt	Sprinklers (Talus I)
Thinning (Talus III/IV)					Planting woody species
					Prescribed fire (to encourage birch)

Predictive model

To simplify the prototyping process, we began with a quantitative evaluation of a limited set of management portfolios (P1& P4; Table 1).

<u>Quantitative investigation of a limited set of portfolios and a single objective</u>
To inform our decisions, we used preliminary results from a simple two-species occupancy model which produced estimates of overall occupancy probabilities for *P. shenandoah*, and estimates of occupancy probabilities in each talus type. This model analyzed the effects of competition with *P. cinereus*, habitat type, and detection probabilities on the occupancy of *P. shenandoah*. For these models, we assumed a constant occupancy and detection probability over time and did not include environmental variation (e.g. temperature or humidity) due to lack of

available data before the structured-decision making workshop. These details will be included in the modeling effort following the workshop. We developed two transition matrices (Fig 2) to account for structural uncertainty. One transition matrix predicted the effect of management that created warmer and drier talus habitat types, without considering the effect of climate change. The other transition matrix included our expectation about how climate change may affect the four talus habitats. Recall that talus type was used as a convenient metric as it is presumed to be a proximate variable for temperature and humidity.

Using estimates of future climate scenarios (Fig 3), we predicted shifts in the talus types in 30 years. This modeling approach allowed us to assess how climate change and management strategies would interact as portfolios were compared. According to the no-climate change model (Model A in Fig. 2), P1 (portfolio 1) management is predicted to improve *P. shenandoah* occupancy (0.43) (Fig 2). According to the climate change model (Model B in Fig. 2), under the P4 management alternative, *P. Shenandoah* is predicted to decline (0.28); this is a result of the high transition rates from talus type II to type I predicted under climate change (0.9), and low *P. shenandoah* occupancy in talus type I (Fig 2). We determined that management must therefore consider the impact of climate change on the habitat.

The analysis exposed some possible unintended consequences. For this example, a focus on management to create talus habitat which was most suitable for *P. shenandoah* would not be the best strategy if climate change is incorporated, as management would exacerbate the number of suitable (i.e., type II and III talus) habitats which were available in *t* to transition to 'unsuitable' (i.e., type IV talus) in *t+30*.

Figure 2. Transition matrices (showing transition rates between talus types) developed to evaluate the response of both *P. shenandoah* and *P. cinereus* occupancies to alternative management portfolios and under different climate scenarios. The columns represent the state *r* of the system (in talus type 1-4) at time *t*, while rows represent the state of the system (talus type) in *t+30*. Matrix entries are the probabilities of transitioning from state *r* to state *s* between *t* and *t*+30. Model A shows the effects of management portfolio P1 (i.e., reduce competition through microclimate habitat manipulation) under no climate change on *P. shenandoah* and *P. cinereus* occupancies. Model B shows the response to management portfolio P4 (i.e., status quo) under climate change. Occupancy of each species at the end of the 30-year period is indicated (boxed), and is compared to occupancy estimated from 2007-08 data (*P. shenandoah*: 0.36; *P. cinereus*: 0.83).

Model A: No climate change. Management Portfolio P1.

		t					pshen	pcin
initial n	t+30	1	2	3	4	t+30	psi(talus)	psi(talus)
1	1	1	0	0	0	1	0.1	0.1
46	2	0	1	0.8	0.2	87.2	0.5	0.77
43	3	0	0	0.2	0.5	25.6	0.3	0.85
34	4	0	0	0	0.3	10.2	0.2	0.89
							0.43	0.79

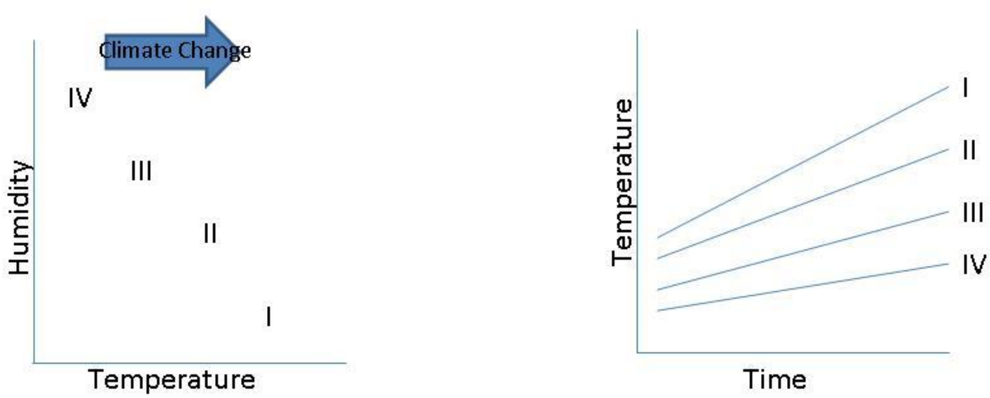
Model B: Climate change. Management Portfolio P4.

		t					pshen	pcin
initial n	t+30	1	2	3	4	t+30	psi(talus)	psi(talus)
1	1	1	0.9	0	0	42.4	0.1	0.1
46	2	0	0.1	0.7	0	34.7	0.5	0.77
43	3	0	0	0.3	0.6	33.3	0.3	0.85
34	4	0	0	0	0.4	13.6	0.2	0.89
							0.28	0.58

no uncertainty

Figure 3. Expected climate change effects on the system, elicited from climate specialist participants De Wekker and Lee. These effects are tentative, ignoring prediction uncertainty. The top panel shows the talus type (I-IV), initial estimates of *P. shenandoah* occupancy per talus type, current relative expected conditions in each talus type (Temperature [Temp], Variability [in climate variables], and relative Humidity), and the effect of climate change on Temperature, Variability and Humidity in the period 2000-2030. Bottom left panel shows the position of each talus type on a temperature/humidity gradient, and the directional effect of climate change acting primarily on temperature. Bottom right panel illustrates the differential effect on each talus type expected under climate change; talus type I warms proportionally more than type IV.

Talus	ΨPshen	Temp	Climate 2030 effect	Variability	Climate 2030 effect	Humidity	Climate 2030 effect
I	0.1?	High	In crease temperatures ↑	high	Increase variability (uncertain) ↑	Low	Negligible change in average
II	0.5	Med high				Med low	
III	0.3	Med low				Med high	
IV	0.2	low		Low		High	



Future modeling directions

Following the workshop, we will improve the species occupancy models by incorporating down-scaled climate data directly into the models for predicting *P. shendandoah* occupancy. This will enable us to provide an explicit link between habitat conditions and management actions, *P. shenandoah* and *P. cinereus* occupancy, and changes in the species' distributions under future climate scenarios. To further refine the '*P. shenandoah* persistence' objective, we will also undertake a population viability analysis for *P. shenandoah*, which will link occupancy with the expected probability of persistence. The resulting model can then be used for predicting population viability under future climate scenarios, varying levels of environmental variation, environmental autocorrelation, and competition with *P. cinereus*. It will also be used to investigate the effects of different management actions and various intensities of these actions on the population persistence of *P. shenandoah*.

Decision Analysis

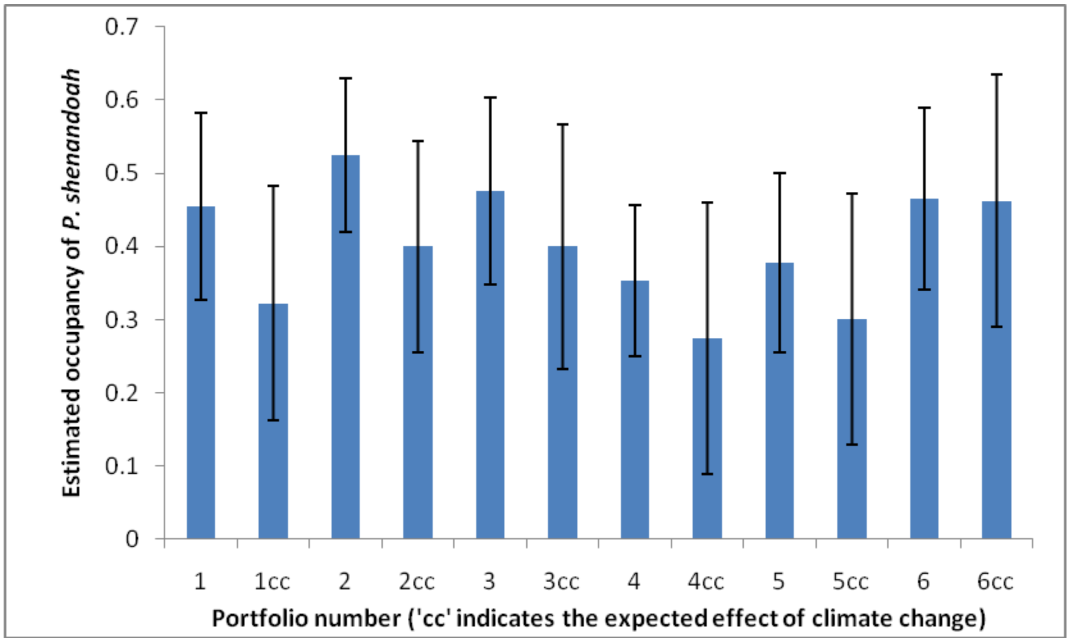
Because the initial modeling approach focused exclusively on the *P. shenandoah* objective and allowed a quantitative evaluation of a limited number of portfolios, we broadened the analysis to include all four fundamental objectives and a wider range of management portfolios. To do this we used a common 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 compare management actions or portfolios and evaluate tradeoffs among multiple attributes, which are linked to the objectives. An analysis of the consequence table identifies the optimal decision based on the relative performance of each management portfolio with respect to the fundamental objectives and takes into account the relative importance of each objective as determined by the decision maker. Uncertainty in predicted performance can be incorporated into the analysis.

Prediction and uncertainty

There are many potential sources of uncertainty, including parametric and structural uncertainty, which might affect this decision. For the purpose of this workshop and to be consistent with the rapid prototyping, we focused on three sources of uncertainty. First, there is uncertainty in the magnitude and direction of climate change. Second, there is uncertainty in the effect of climate change on occupancy. Third, there is uncertainty in the relationship between occupancy and population persistence. In the absence of empirical estimates, we turned to elicitation to represent these uncertainties. Elicited predictions can be used for an initial assessment of the influence of uncertainty on decisions and provide a basis for updating when new data are available from future monitoring (Burgman 2005).

Workshop participants provided expert opinion on the occupancy of Shenandoah salamander that would result from the full suite of management portfolios (Fig 4). Occupancy estimates were generated for two divergent scenarios, one assuming a climate change effect and another assuming climate change would not occur. We also used an elicited relationship between occupancy and probability of persistence (as well as the elicited ranges in the relationship; Fig 1) to evaluate the influence of management portfolios on occupancy (and ultimately, persistence) of *P. shenandoah*. The climate change effect was considered to be consistent with the shifts in talus types described previously in Figure 3. Participants provided expert predictions under each climate change scenario: 1) the expected occupancy, 2) the range of occupancy, and 3) the confidence level for that range. The ranges were standardized to an 80% confidence interval, and the predictions were averaged among participants (Fig 4). In general, elicited occupancy was predicted to be lower and more variable assuming a climate change effect compared to the no climate change effect scenario (Fig 4).

Figure 4. Elicited mean occupancy (and 1 SD) of *P. shenandoah* resulting from implementation of each portfolio (1-6 on x-axis; see Table 1), with and without climate change (indicated 'cc' after each portfolio number on x-axis). It is noteworthy, but anticipated, that the uncertainty is greater when considering the climate change scenario.



We then used the previously elicited relationships between occupancy and probability of persistence (Fig 1) to translate the predicted occupancy into probability of persistence. Our resulting range of persistence probabilities for *P. shenandoah* allowed us to assess preliminarily which management portfolios would have the largest impact on population persistence and to determine if climate change would affect the decision by altering the ranked performance of the various management portfolios. Uncertainty in predicted probability of persistence is the combination of uncertainty in predicted occupancy (as represented by the standard deviation around the estimated occupancy in Fig. 4) and the uncertainty in the relationship between occupancy and persistence.

We computed probabilities of persistence under 9 different combinations of uncertainty - including 3 levels of response to management and 3 levels of uncertainty in the relationship between *P. shenandoah* occupancy and probability of persistence (Table 2). The 3 levels of response to management came from the expected or mean response and the two 80% confidence limits (Fig 4). The 3 levels of certainty in the relationship between occupancy and persistence come from the 3 curves in Fig 1. To find the worst case and best case, we found the lowest and highest probability of persistence across all management portfolios and both climate change scenarios. The lowest persistence always occurred for the climate change scenario and the highest persistence always occurred for the no climate change scenario.

Possibility		**Pr(Persistence)**	
Occupancy Response to Management	Occupancy Transformation to Persistence	Worst	Best
Low	Low	0.07	0.62
Expected	Low	0.47	0.7
High	Low	0.69	0.78
Low	Expected	0.09	0.81
Expected	Expected	0.62	0.85
High	Expected	0.84	0.89
Low	High	0.1	0.91
Expected	High	0.7	0.95
High	High	0.94	0.99

Table 2. Probabilities of persistence (worst- and best-case expectation) under 9 different combinations of uncertainty in a) occupancy response to management (column 1, see also Fig 4) and b) the occupancy-persistence relationship (column 2, see also Fig 1). Probability of persistence was computed across all management portfolios and both climate change scenarios.

An exemplary consequence table is shown in Appendix I for the case defined by the expected response to management (means in Fig 4) and expected relationship between occupancy and persistence (middle curve in Fig 1). The two climate change scenarios are represented by the predictions in the first two rows of the consequence table. The lowest probability of persistence corresponds to portfolio 'P4' under a climate change effect, and the highest probability of persistence corresponds to portfolio 'P2' under no climate change. Portfolio 'P4' is status quo and 'P2' is range expansion by assisted colonization.

Weighting the objectives

To investigate the tradeoffs among the four objectives [(1) maximize persistence of *P. shenandoah*, (2) maximize adherence to park policy, (3) maximize public acceptance of management, and (4) minimize total cost of management)], we used swing weighting to elicit weights on the objectives from the decision maker, who in the workshop was represented by Wofford, in consultation with Dean. We used swing weighting, which is a technique to represent decision makers' values in the decision analysis while accounting for the range in performance expected across management actions (Goodwin and Wright 2004). Swing weights depend on the magnitude of performance differences across alternative actions. For example, an objective would tend to be assigned a low weight if its measurable attribute is predicted to change little across management actions, all else being equal.

We first weighted the three objectives related to park policy (minimize cost, adhere to policy, maximize public acceptance) because the attributes for these objectives did not vary across uncertainty in climate change effect. The decision maker was asked if only one of the three objectives could be changed from the worst to the best case (e.g., from high costs to no additional costs), while the other two objectives remained at their worst case, which objective would he choose? The two remaining objectives were then compared similarly, and the objectives were assigned ranks reflecting the relative importance of the three objectives.

We then determined the swing weight on the persistence objective for the extreme ranges in probability of persistence. The widest range in predicted persistence occurred for a low management response and a high occupancy-persistence relationship. That combination resulted in a worst case of 0.1 persistence probability and a best case of 0.91 persistence probability across the climate change uncertainty (Table 2). The narrowest range in predicted persistence occurred for a high management response and a high occupancy-persistence relationship. That combination resulted in a worst case of 0.94 and a best case of 0.99 persistence probability across climate change uncertainty (Table 2). We determined the swing weight for both of these extreme ranges and also for the 'expected' case (i.e., an expected management response and an expected occupancy-persistence relationship), which resulted in worst to best cases of 0.62 and 0.85 persistence probability across the climate change uncertainty (Table 2). The swing weights for all objectives are shown in Table 3.

Objectives	Expected range	Widest range	Narrowest range
Maximize persistence	36	65	3
Adhere to park policy	40	22	61
Maximize public acceptance	8	4	12
Minimize cost	16	9	24

Table 3. Swing weights determined for three ranges of uncertainty in the predicted probability of persistence. The relative weights among the park policy, public acceptance, and cost objectives are constant among the three ranges; absolute weights vary according to the weight assigned to the persistence objective. The weights are scaled to sum to 100.

Weights were incorporated into the final score for the performance of each alternative with respect to the four fundamental objectives, using consequence tables. We developed 18 consequence tables, including the combination of management effectiveness (3 levels - low, expected, high), the probability of climate change (2 levels - no change, change likely), and the relationship of occupancy to persistence (3 levels - low, expected, high). Scores were normalized across the two climate change scenarios within a management effectiveness scenario and an occupancy-persistence relationship scenario.

Final analysis

In general, portfolio 2 (expand range) and portfolio 4 (status quo) scored higher than the other portfolios (Appendix II). We then performed a sensitivity analysis on the weight allocated to the 'maximize *P. shenandoah* persistence' objective under both the 'no climate change' and 'climate change' scenarios. We identified the point at which the optimal decision switches from the 'do nothing/status quo' management (portfolio 4) to the active management (via portfolio 2) alternative (Fig 5). The point identified (~0.2) was far below the likely weight that would be allocated to the 'maximize *P. shenandoah*' objective (the swing weighting exercise suggested that the salamander objective would likely be weighted much higher); thus, active management is considered a better decision than the status quo (Table 3). This indicates that if the decision makers consider that salamander persistence is at least as important as adherence to park policy then the decision is robust to the expected effect of climate change (Fig 5). In other words, active management is indicated for both climate change scenarios.

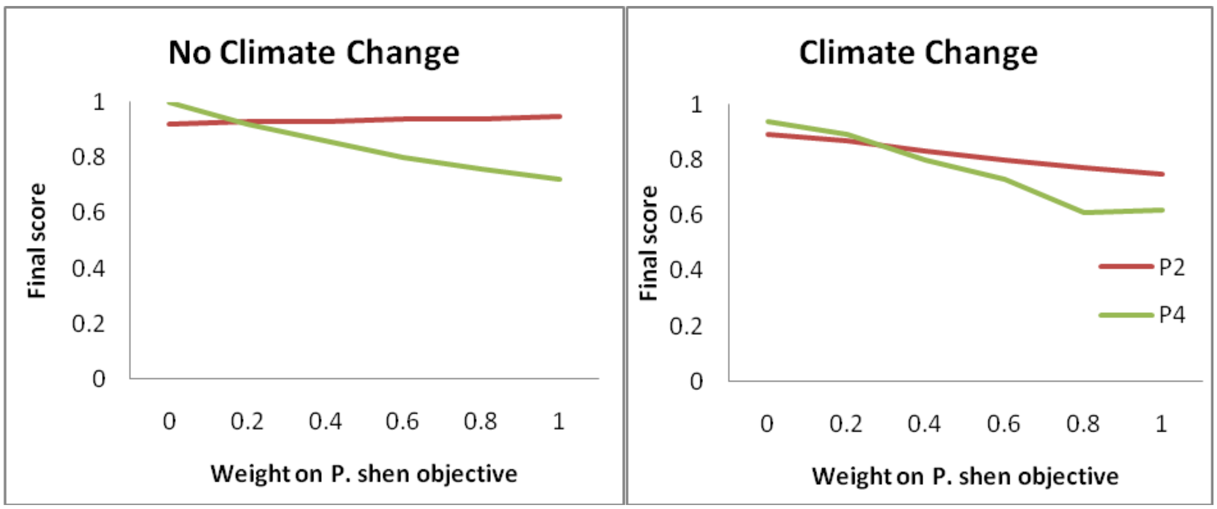


Figure 5. Sensitivity analysis under the 'Expected' (i.e., mean) management effectiveness and 'Expected' occupancy-persistence relationship, contrasting the 'Status quo/Do nothing" portfolio (P4) with the active management portfolio (P2).

Uncertainty

Uncertainty was present in all aspects of this decision problem. The ecology of the species and the expectation of future climate conditions under climate change were two major sources of uncertainty identified prior to the workshop. The relationship between *P. Shenandoah* occupancy and persistence and the effects that each management alternative may have on the persistence of *P. shenandoah* were sources of uncertainty identified during the workshop. At the conclusion of the workshop, participants were in agreement that these sources of uncertainty were indeed important to the decision, and efforts to reduce these uncertainties will proceed. However, after accounting for substantial sources of uncertainty in the decision analysis, the preliminary indication is that some active management should be considered if salamander persistence is an important objective.

We plan to address uncertainty in four ways: first, we are designing a set of experiments which will elucidate the ecology of *P. shenandoah*, particularly with respect to our expectation about how climate variables (temperature and humidity) may influence competition with *P. cinereus*. Second, we will combine field observations of temperature and humidity to calibrate downscaled climate models, which will provide site-specific estimates of future climate conditions under a range of likely climate scenarios. Third, we plan to develop a PVA to reduce the uncertainty about the relationship between occupancy and persistence. Finally, we will conduct additional surveys outside of the known distribution (described in Highton and Worthington 1967) to determine the true range limits of the species. Reducing these uncertainties will help inform the effect that the alternative management actions may have on *P. shenandoah* occupancy.

Though we focused on a one-time decision made on a 30-year timeframe, we will expand the decision framework into an iterative decision cycle which will more closely match the existing decision timescale in the park (annually, or up to every 5 years when compliance documents are reviewed) and will match temporal scales of future monitoring plans. We will develop an adaptive management plan outlining steps to protect the Shenandoah salamander from climate change impacts, and a monitoring plan designed to reduce uncertainty in the relationship between climate variables, competition with *P. cinereus,* changes in distribution of the Shenandoah salamander, and the effect of management on *P. shenandoah* persistence.

Discussion

Value of decision structuring

Participants agreed that the process was extraordinarily informative. Having members of the group present in one location for "face-time" provided the appropriate context for working through a difficult problem. The structure itself provided a formal means to make inquiries into assumptions, to support science based decisions, and to challenge individual perceptions of "the problem". This formal structure, which is explicit, transparent, and interactive, provides the means to solicit information from participants. As such, results from the process are supported by those involved in development of the decision.

Further development required

Efforts during our week at the workshop largely involved solicited opinions from experts. This relatively speedy (though not painless) procedure allowed the prototype process to proceed. Nevertheless, future work entails developing models to incorporate more explicitly the quantitative information we have available (or will be collected in the coming years). The workshop also revealed uncertainties about the species' distribution and biology that will be addressed in future field work. A tremendous number of simplifications/assumptions were made to complete the prototyping process (see below) and these will ultimately have to be addressed. Finally, the NPS decision makers were not present at the workshop and initiating future involvement and understanding by NPS decision makers will be needed.

Prototyping process

Participants were surprised at how difficult it was to define our objectives. We found that explicitly defining objectives and available alternatives as a group allowed integration of everyone’s vision of the problem, especially as we had a diverse group of participants who had knowledge and experience with different aspects of the problem. The explicit recognition of the nature and pervasiveness of unknowns at one point made it seem that the problem was intractable, but the SDM process allowed us to acknowledge this uncertainty and proceed. For the climate experts, a difficult part was the translation of physical processes affecting the maximum and minimum temperature into uncertainties that go into the decision making process. We made a lot of guesstimates of the uncertainty, also caused by the early stage of our research into climate downscaling. It was eye opening that some of the final decisions would not be very sensitive to these guesstimates. Obtaining a better sense of the importance of various types of information in the decision making process will help direct future research activities that aim to reduce climate change uncertainty. Completing the process in one week resulted in the need to simplify reality at every step of the process, except, perhaps, in creating the initial problem definition and objectives. This was concerning, but ultimately, we wouldn't have developed a prototype without those simplifications. Of course, the benefit of the prototype is that it provides a foundation for moving forward, and it did meet that purpose.

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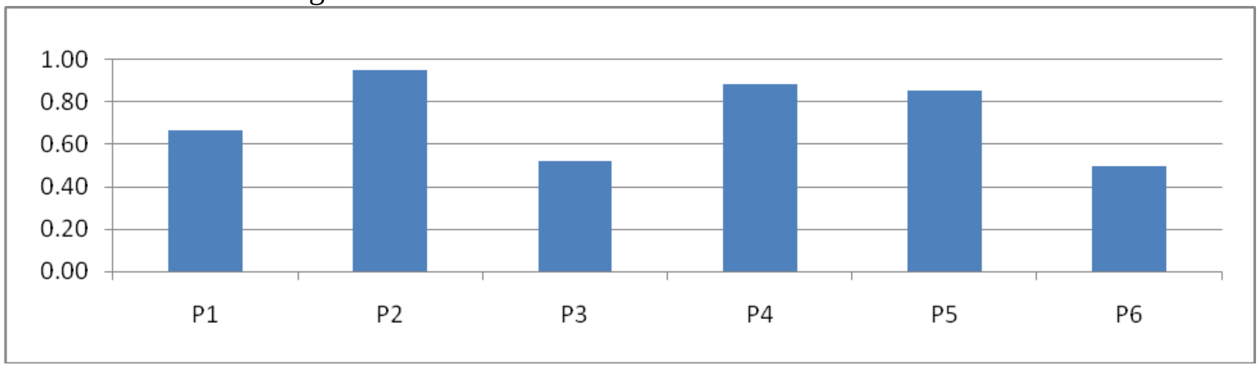
Appendix I. Consequence table showing expected predicted probability of persistence along with attributes for other objectives across the 6 management portfolios, described in Table 1, for both climate change scenarios consistent with the shifts in talus type presented in Figure 3.

		Treatment (Alternatives)						
Objectives	**Goal**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**Units**
***P. shen* persistence | no climate change**	Max	0.83	0.85	0.84	0.78	0.81	0.83	probability of persistence
***P. shen* persistence | climate change**	Max	0.71	0.81	0.81	0.62	0.67	0.83	probability of persistence
Adhere to Park policy	Max	2	4	2	4	4	1	5 pt scale 1 = intolerable, 5 = tolerable
Public acceptance	Min	3	1	3	1	5	4	5 pt scale for increasing neg phone calls
Cost	Min	2,500	30,000	90,000	0	10	10,000	dollars per acre per year

Appendix II. Results from Simple Multi-attribute Rating Technique. Weighted and standardized scores for each management portfolio (see Table 1 for description) based on the expected response to management (means in Fig 4) and expected relationship between occupancy and persistence (middle curve in Fig 1). Scores were standardized within an attribute and then combined across attributes using weights assigned to each objective. Comparisons are shown for (A) a no climate change scenario and (B) a climate change effect consistent with the shifts in talus type presented in Figure 3. The portfolios can be summarized as P1 = reduce competition by microclimate; P2 = expand range by assisted colonization; P3 = reduce competition directly; P4 = status quo; P5 = eliminate direct human influence; and P6 = expand range by microclimate.

A. No climate change effect



B. Climate change effect