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Developing a conservation strategy to maximize persistence of an endangered freshwater mussel species while considering management effectiveness and cost

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Abstract: We used a structured decision-making process to develop conservation strategies to increase persistence of Dwarf Wedgemussel (*Alasmidonta heterodon*) in North Carolina, USA, while accounting for uncertainty in management effectiveness and considering costs. Alternative conservation strategies were portfolios of management actions that differed by location of management actions on the landscape. Objectives of the conservation strategy were to maximize species persistence, maintain genetic diversity, maximize public support, and minimize management costs. We compared 4 conservation strategies: 1) the 'status quo' strategy represented current management, 2) the 'protect the best' strategy focused on protecting the best populations in the Tar River basin, 3) the 'expand the distribution' strategy focused on management of extant populations and establishment of new populations in the Neuse River basin, and 4) the 'hybrid' strategy combined elements of each strategy to balance conservation in the Tar and Neuse River basins. A population model informed requirements for population management, and experts projected performance of alternative strategies over a 20-y period. The optimal strategy depended on the relative value placed on competing objectives, which can vary among stakeholders. The protect the best and hybrid strategies were optimal across a wide range of relative values with 2 exceptions: 1) if minimizing management cost was of overriding concern, then status quo was optimal, or 2) if maximizing population persistence in the Neuse River basin was emphasized, then expand the distribution strategy was optimal. The optimal strategy was robust to uncertainty in management effectiveness. Overall, the structured decision process can help identify the most promising strategies for endangered species conservation that maximize conservation benefit given the constraint of limited funding.

Key words: freshwater mussel, strategic conservation, decision analysis, structured decision making, Dwarf Wedgemussel, *Alasmidonta heterodon*, endangered species

Conservation strategies for endangered species must be developed in the challenging context of limited funds, incomplete species information, and uncertainty in projecting outcomes. The practical reality is that costs must be considered when developing strategic conservation because identifying a strategy is of little advantage when funds are not available under any circumstances for implementation (Burgman 2005, Bottrill et al. 2008, Joseph et al. 2008). In addition, a professional obligation exists to identify the least costly option among those that achieve the same conservation benefits. Sparse data often require reliance on expert knowledge to evaluate consequences of

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alternative strategies (Drescher et al. 2013). Last, uncertainty must be considered when projecting the consequences of alternative strategies because uncertainty can obscure which strategy is best (Runge et al. 2011).

The Dwarf Wedgemussel (*Alasmidonta heterodon*) was federally listed as endangered in 1990 because of habitat degradation and a declining population (USFWS 2013). The current range of Dwarf Wedgemussel extends from New England to North Carolina. Dwarf Wedgemussel appears to have been extirpated from Canada. Populations in the Connecticut and Delaware Rivers appear stable. However, more southern populations in Maryland, Virginia, and North Carolina are small and vulnerable. North Carolina is the southern extent of the species' historical and current distribution, which heightens the importance of species conservation there. The taxonomy of Dwarf Wedgemussel is the subject of ongoing research, and genetic studies indicate that North Carolina populations are genetically unique within the species (Shaw et al. 2006, T. King [US Geological Survey], unpublished data). Maintaining viable populations in North Carolina is considered critical to the recovery of the species (USFWS 2013).

That Dwarf Wedgemussel populations in North Carolina are declining is evidenced by low densities and low recruitment (USFWS 2013). In North Carolina, Dwarf Wedgemussel is known from 5 watersheds, 2 in the Tar River basin (Upper Tar River, Fishing Creek basin), and 3 in the Neuse River basin (Upper Contentnea Creek basin, Little River, Swift/Middle Creeks) (Fig. 1). Small fragmented populations of questionable viability exist in ~18 mainstem streams and tributaries within these basins. Threats related to destruction, modification, and curtailment of its habitat have severely affected Neuse River basin populations, and populations in the upper Tar River basin appear to have been affected by recent droughts. Rarity of populations, infrequent quantitative surveys, and uncertainty regarding conservation targets and underlying limiting factors complicate effective management. Funding is limited and often linked to actions to mitigate impact associated with federally funded projects, such as road and bridge construction or dam modification.

Current management of Dwarf Wedgemussel in North Carolina tends to be in reaction to pending or developing threats. Tools are emerging or are being newly considered

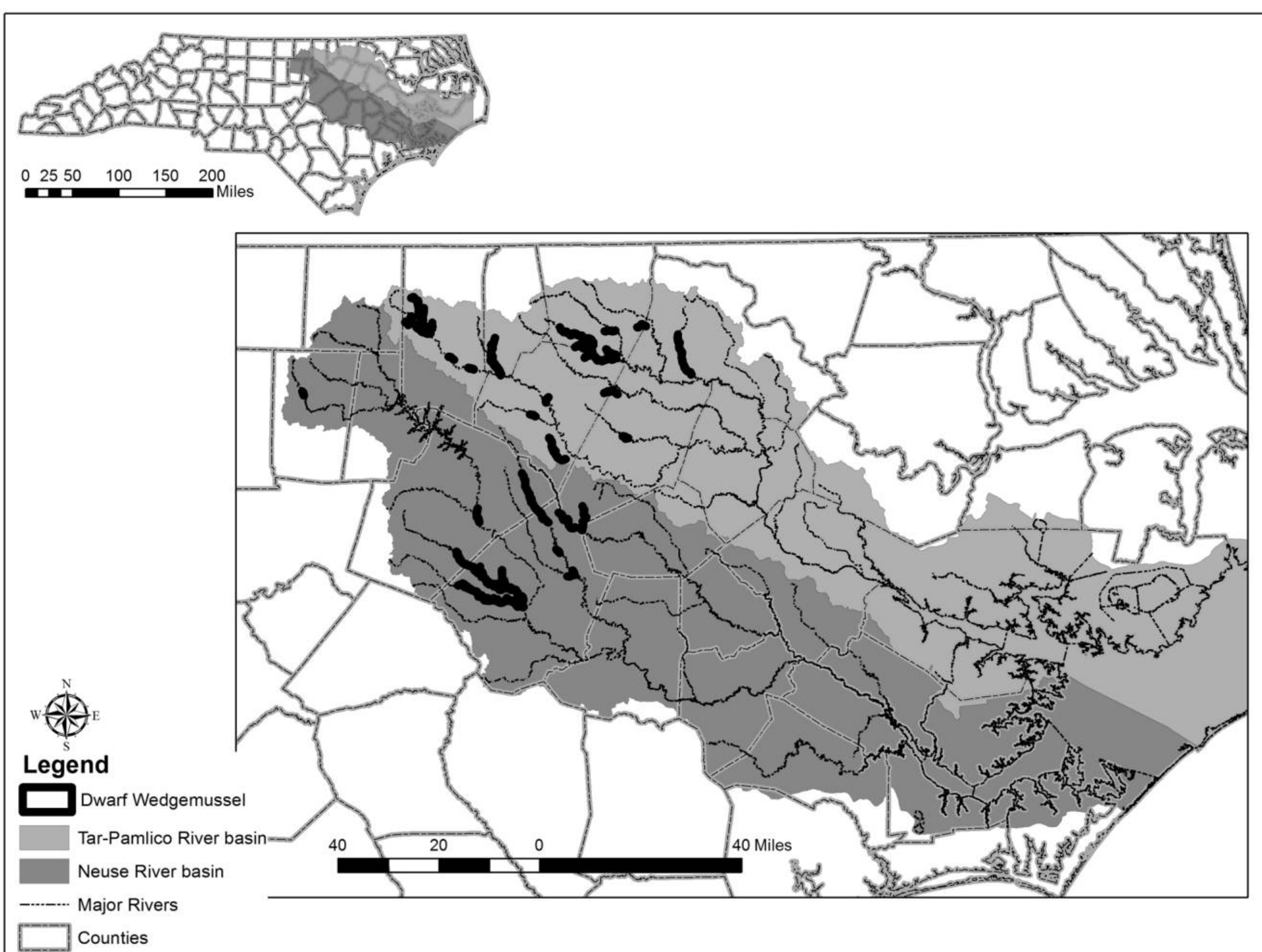

Figure 1. Locations of stream reaches with Dwarf Wedgemussel in North Carolina.

(e.g., propagation, translocation, and habitat protection guided by suitability modeling) that provide opportunities for management to become more proactive (Jones et al. 2012). However, which action or combination of actions (strategies) would perform best at achieving conservation objectives is unclear. In fact, current management might be as effective as alternative strategies when all objectives are taken into account.

A structured decision-making process can be used to compare how well management strategies meet multiple—often competing—conservation objectives (Gregory et al. 2012a, Conroy and Peterson 2013). The application of structured decision processes to natural-resource management and conservation is increasing as its utility for assisting decision making in the face of competing objectives and uncertainty is being documented (Gregory and Long 2009, J. P. Martin et al. 2011, Gregory et al. 2012b, Conroy and Peterson 2013). The structured decision-making process is values-focused and deconstructs the decision problem into universally recognizable components that can be deliberated on by stakeholders, resource experts, and analysts. Transparency and explicitness are hallmarks of a structured decision-making process. Identification of fundamental objectives is the first component to be worked on after the problem is defined and framed. Development of creative alternatives follows identification of conservation objectives. Optimal solutions can be found by evaluating the alternative management actions or conservation strategies that best meet the conservation objectives.

A series of workshops was held to bring together a team of biologists and managers from US Fish and Wildlife Service (USFWS), North Carolina Wildlife Resources Commission, and others with expertise on management and ecology of Dwarf Wedgemussel in North Carolina. Their goal was to identify the conservation strategy that best meets conservation objectives. Following a structured decision-making process, the team first considered the objectives related to conservation of Dwarf Wedgemussel in North Carolina. Second, the team identified the conservation strategies that could feasibly address the objectives. Next, the group built predictive models and conducted tradeoff analyses to compare alternative conservation strategies with respect to how well they meet the conservation objectives or targets. Here, we present the outcome of this process.

METHODS

Two structured decision-making workshops and several conference calls were attended by biologists from USFWS, North Carolina state agencies, US Geological Survey (USGS), and other partners involved in developing Dwarf Wedgemussel conservation strategies along with technical experts who have knowledge of life history, abundance and distribution, and conservation techniques for the species. The process began with identification of objectives followed by a discussion of what factors influence objectives, including the factors that limit Dwarf Wedgemussel abundance and distribution. The next step was to list the management actions that could be part of a conservation strategy. Alternative strategies were created to address those limiting factors in an efficient manner with each alternative representing different levels of effort allocated among the management actions.

Performance measures (attributes) were specified for each objective, and performance of each alternative strategy was projected over a 20-y period to rate and compare strategies. Underlying processes, such as climate, were assumed to be stationary over the 20-y period. Attributes for species persistence, based on abundance, distribution, and recruitment, were evaluated first at the stream-reach scale and then at the basin scale. The abundance attribute was projected on a categorical scale: −1 = absence and not recoverable, 0 = absence but recoverable including locations where Dwarf Wedgemussel have never been found but habitat appears to be suitable, 1 = presence but below the limit where detection is likely given feasible survey effort, 2 = rare (i.e., 0–2 individuals detected in an 8-person-hour [ph] search), 3 = moderate abundance (i.e., 3–10 detected in an 8-ph search), and 4 = abundant (i.e., >10 detected in an 8-ph search). Dwarf Wedgemussel in North Carolina is an extremely rare mussel species with a low encounter rate. The abundance scale used here is relevant to Dwarf Wedgemussel in North Carolina, but would not be relevant to other more abundant species. Occupancy, a proxy for distribution, was binary and indicated whether a stream reach was occupied (1) or not occupied (0). Recruitment was projected as a likelihood of recruitment in a stream reach within the previous 3 y.

At the basin scale, the species attributes were summations of the reach-level attributes. For example, the basin-level attribute for distribution was the sum of reach-level occupancy. The attribute for genetic diversity was categorical and based on the probability of maintaining genetic diversity: 0 if the probability was <0.8 and 1 if the probability was ≥0.8. The threshold probability of 0.8 was arrived at by consensus reflecting the risk tolerance of the team.

The attribute for public support was on a categorical scale ranging from −2 (active opposition) to +2 (active support) with neutral public opinion at the midpoint. The attributes for cost were in units of $US1000 totaled over 20 y. The costs for state and federal agency staff and operations were kept separate from costs for land acquisitions, grants, and conservation banks.

Projected performance was elicited from the team using a modified Delphi process, which is commonly used to acquire group judgments (Gregory et al. 2012a, McBride et al. 2012). The team was asked to respond as individuals after a facilitated discussion to clarify each question being asked. This response step was followed by presentation and discussion of individual responses, and the team was given the opportunity to revise their responses based on insights gained during group discussion.

Population model

We built a stage-based population model to inform decisions regarding augmentation of existing populations (e.g., to overcome Allee effect or depensation) and reestablishment of historic populations. Vital rates (e.g., survival and fecundity) were taken from existing data and literature on Dwarf Wedgemussel, if available, or from studies of other freshwater mussel species. Dwarf Wedgemussel life expectancy is 10 to 12 y with first reproduction at age 3 (Michaelson and Neves 1995). Number of Dwarf Wedgemussel glochidia per adult female was based on data from captive propagation work for the species and expected to be 3500 with a spread of 2000 to 5000 (CBE and B. Wicklow [Saint Anselm College], personal communication). Recently reported fecundity of 2661 (2067–2997) for a sample of 3 Dwarf Wedgemussels (Haag 2013) is within the range used in the population model. Frequency of gravidity was estimated to be 0.5 probability of being gravid in a given year with spread of 0.11 to 0.64 based on data for Dwarf Wedgemussel (in Massachusetts) and other species (Bauer 1987, McLain and Ross 2005). Sex ratio was assumed to be equal at glochidial stage. Survival of glochidial larvae to transformation was approximated to be 0.0006 based on studies of *Margaritifera laevis* (Akiyama and Iwakuma 2007) and *Anodonta grandis* (Jansen and Hanson 1991). Adult annual survival was taken to be 0.56 based on estimates for the Dwarf Wedgemussel from Tar River (Michaelson and Neves 1995). No estimates of juvenile survival are available, so we examined scenarios of juvenile survival less than, equal to, and greater than adult survival. The model included diminished adult survival for ages >10 y to simulate senescence and assumed survival for ages >13 = 0. We assumed spawning occurred in late summer with glochidial release in March to June (Michaelson and Neves 1995, McLain and Ross 2005), and the model was structured for a birth pulse with a prerelease census.

Caswell (2001) found in a sensitivity analysis that population growth was most sensitive to early life-stage survival (ages 0, 1, and 2) and fecundity during the 1st y of maturity (age-3 fecundity). Elasticity, which measures the proportional effect of parameter change on population growth, for these most sensitive parameters was ~0.2 and was an order of magnitude higher than for the next most sensitive parameters, which were age-3 survival and age-4 fecundity, each with elasticities ~0.02. Elasticities for all other parameters were ≤0.002.

The model included age-specific release of cultured animals for the purpose of evaluating culture and release as a management action. The ratio of survival of cultured to wild animals of a given age and the number of years of

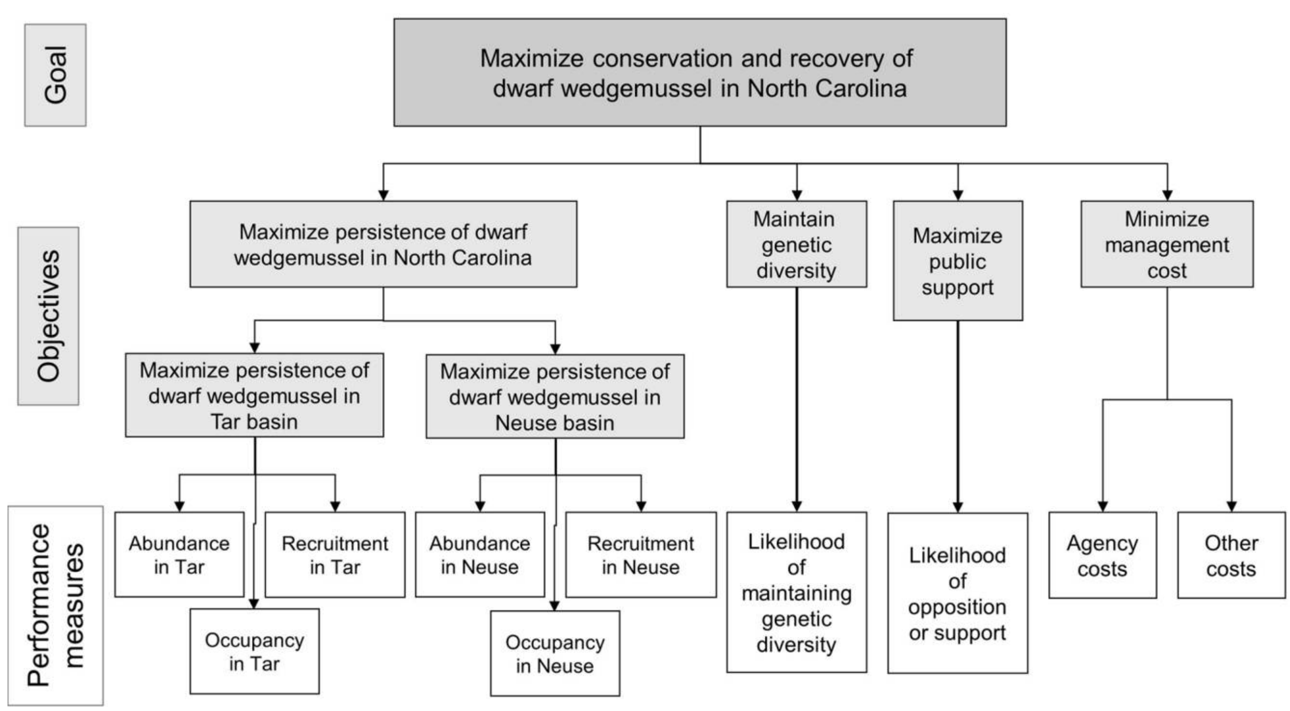

Figure 2. Objective hierarchy for conservation of Dwarf Wedgemussel in North Carolina.

release could be specified. Population trajectories were simulated in Excel via the *@Risk* add-on (version 5.7; Palisade Corporation, Ithaca, New York).

Tradeoff analyses

The simple multiple-attribute rating technique was used to evaluate tradeoffs and compare alternatives (Goodwin and Wright 2007). Our alternatives were the 4 conservation strategies. Performance measures were elicited and then normalized to a scale of 0 to 1 representing worst to best, respectively. Normalized ratings were multiplied by objective weights and summed to arrive at an overall rating for each conservation strategy. The overall rating for the i^{th} alternative conservation strategy (V_i) can be expressed as:

$$V_i = \Sigma_{j=1}^{m} w_j V_{ij}, \qquad \text{(Eq. 1)}$$

where w_j is the weight for the j^{th} objective and V_{ij} is the normalized rating for the j^{th} objective and the i^{th} alternative strategy. The weights (w_j) are *swing weights* (Goodwin and Wright 2007), which reflect the relative importance of an objective and account for the magnitude or degree that an objective would be changed across the range of alternatives being considered. For example, an objective, such as persistence, might have high relative importance, which would indicate high weight, but if the persistence is not projected to differ among the conservation strategies then its objective weight should be relatively low. A conservation strategy with the highest overall rating, i.e., $max(V_i)$, is said to be optimal.

Sensitivity analyses to assess effect of uncertainty on strategy development

Overall ratings can be sensitive to variation in objective weighting and to uncertainty in predictions. Objective weights reflect values, so no single 'correct' objective weighting exists. Objective weights often vary among stakeholder groups or among partnering agencies (Davies et al. 2013). However, it can be helpful to a decision maker to know whether an alternative is optimal across a wide range of objective weightings, i.e., whether the optimal alternative is robust to variation in stakeholder values. Projected performance also carries uncertainty, and it can be helpful to know whether the optimal alternative is robust to prediction uncertainty.

We evaluated sensitivity to variation in stakeholder values by repeating the tradeoff analysis for various objective weights by weighting different objectives or sets of objectives more highly than others. We emphasized an objective (or set of objectives) by assigning twice the weight given to unemphasized objectives and repeated the tradeoff analysis. In separate evaluations, emphasis was placed on overall conservation (i.e., persistence and genetic diversity), statewide persistence, persistence in the Tar River basin, persistence in the Neuse River basin, or cost.

We evaluated sensitivity to prediction uncertainty by repeating the tradeoff analysis across a range of management effectiveness at the basin level. We elicited the estimated probabilities of habitat and population management effectiveness separately for the Tar or Neuse River basins. A probability of management effectiveness <1 indicates that the performance will be partially successful. For example, a probability of 0.5 for population management effectiveness indicates that the change in abundance from status quo will be ½ what would be expected if it were fully effective. In a modified-Delphi approach (Drescher et al. 2013), we elicited and discussed individual judgments on effectiveness. We used the average of the individual judgments as a starting point and repeated the tradeoff analysis for management effectiveness until we reached full effectiveness (i.e., probability of effectiveness = 1). Let x_{ijk} denote the i^{th} performance measure (e.g., level of abundance within a stream reach) for the j^{th} conservation strategy in the k^{th} river basin (either Tar or Neuse River basins). Further, let $j = 0$ for the status quo strategy. Then the performance measure adjusted for management effectiveness is:

$$x^*_{ijk} = x_{i0k} + (x_{ijk} - x_{i0k})P_k, \qquad \text{(Eq. 2)}$$

where P_k denotes the probability of management effectiveness in the k^{th} river basin. For full management effectiveness, $P_k = 1$ and $x^*_{ijk} = x_{ijk}$.

RESULTS

Problem statement

The decision problem was to identify the conservation strategy for maximizing persistence of Dwarf Wedgemussel in North Carolina while minimizing management costs. The strategy is intended to guide conservation agencies toward a management approach that will achieve high conservation benefits in a cost-efficient manner. From a practical point of view, the planning horizon was defined as 20 y, which is ~3 generation times for Dwarf Wedgemussel assuming a 6- to 7-y generation time.

Objectives

The team identified maximizing probability of persistence of Dwarf Wedgemussel throughout its range in North Carolina, maintaining genetic diversity, maximizing public support, and minimizing costs as the fundamental management objectives (Fig. 2). Prior to defining the main conservation objective in terms of persistence, the team contrasted persistence, recovery, and restoration. Persistence is the opposite of extirpation and is a necessary prerequisite to the eventual recovery under the US Endangered Species Act (ESA) defined by the species' long-term survival in the wild usually associated with a reduction in threats and ensured by sufficient species' range and abundance. Restoration implies reaching a benchmark determined by historical levels of population distribution and abundance. Thus, the team viewed persistence as the most relevant way to frame conservation of Dwarf Wedgemussel in North Carolina. The team recognized that to achieve persistence, at least some existing populations must be protected, additional populations must be established to 'spread the risk' through redundancy, and abundance of all populations should be at a level to provide resiliency in the face of current and future threats (Shaffer and Stein 2000, Waples et al. 2013). Persistence will rely on protection and improvement of representative habitats, especially in the headwaters.

Loss of genetic diversity can contribute to reduced persistence, so maintenance of genetic diversity is in one sense a means to achieve persistence. However, the team viewed maintenance of genetic diversity as desirable not only as a means to persistence, but also as a separate fundamentally important conservation objective. Therefore, genetic diversity was included as an independent conservation objective.

Minimizing management costs (equivalent to effective use of funds) is also important in conservation decisions. Maximizing public support is viewed as strategically important because conservation actions are more readily implemented when the public is supportive. Conversely, the lack of public support can be a serious impediment to action.

Alternative conservation strategies

Creating alternative conservation strategies began with an exploration of the factors affecting the fundamental objectives. Factors that limited population growth were discussed and the highest ranked limiting factors at the stream-reach level were identified (Table 1). In the Neuse River basin, the most commonly identified factors were unsuitable physical habitat, Allee effect, and contaminants. In the Tar River basin, the most commonly identified factors were beaver-altered habitat coupled with unsuitable flow, unsuitable physical habitat, and Allee effect. Management actions were listed and conservation strategies were created as portfolios by defining the level of implementation for each action within each strategy (Table 2). Units for level of implementation were either direct measure (e.g., number of propagated juveniles released) or a measure of effort relative to status quo management. For example, if an action's implementation was decreased, the same, or increased relative to status quo, then the effort was 0.5, 1.0, or 1.5, respectively. If an action was not implemented, then the effort was 0. Management actions fall within 4 management types:

1. ***Population management*** Actions that directly affect populations, such as augmentation (i.e., release of individuals of a species into a river reach where it currently exists), reintroduction (i.e., release of individuals of a species into suitable historical habitat from which it has been extirpated, and where natural recolonization cannot reasonably be anticipated), or salvage (i.e., moving remaining individuals of a species from a location into captivity because of impending threats). Augmentation or reintroduction could be carried out using propagated animals or animals translocated from a source population. Augmentation and reintroduction might affect genetic diversity. Risk of disease transmission is controlled by following established protocols. The population model was used to determine the probability of persistence at 20 y based on release of propagated animals for 10 consecutive years. Release of 1000 and 2000 3-y-old animals to augment a population and 2000 and 3000 3-y-old animals to establish a population was expected to result in a reasonable chance of persistence (Table 3). Low extant abundance was assumed for augmentation (Table 3). Thus, required releases for establishing a population were similar to (i.e., 1.5×) the requirement for augmentation.
2. ***Habitat management*** Actions that affect habitat, such as regulation or ordinances, acquisition of land through purchase, establish conservation easements, restoration, and beaver control.
3. ***Monitoring and research*** Actions that increase information and contribute to learning for the purpose of increasing conservation benefits or reducing management costs.
4. ***Partnership building and outreach*** Actions that affect public support, such as outreach or public education.

The spatial scale differed among management actions. At the large spatial scale, application of new regulations for habitat protection would be most likely to apply to the basin level. At the medium spatial scale, beaver control (which falls under habitat restoration) would be applied to the subbasin or stream within basin. At the small spatial scale, augmentation could be applied to a population within a stream or stream reach.

Alternative conservation strategies were designed to address limiting factors (Table 1) and to affect ≥1 of the fundamental objectives in a desired direction (Fig. 2). A conservation strategy comprises individual management actions selected with the aim of emphasizing certain objectives or relying on certain assumptions of how best to achieve the objectives. The team created 3 alternative conservation strategies to status quo management (Table 2).

Table 1. Factors elicited from workshop participants that are thought to be limiting persistence of Dwarf Wedgemussel populations. The limiting factors are listed in order of importance within stream reach. Selection was from the list of threats and ecological factors adapted from Strayer (2008).

Basin	Stream reach	Limiting factors
Neuse River	Swift Creek including Little and White Oak Creeks	1. Unsuitable physical habitat
		2. Allee effect
		3. Low water quality because of contaminants
	Middle Creek	1. Unsuitable physical habitat
		2. Allee effect
		3. Low water quality because of contaminants
	Little River (Wake/Johnston)	1. Allee effect
		2. Beaver alteration of habitat
		3. Lack of dispersal
		4. Unsuitable physical habitat
Tar River	Shocco Creek (and tributaries)	1. Beaver alteration of habitat
		2. Unsuitable flow
		3. Unsuitable physical habitat
		4. Allee effect
	Maple Branch	1. Beaver alteration of habitat
		2. Unsuitable flow
		3. Unsuitable physical habitat
		4. Allee effect
	Long Branch	1. Beaver alteration of habitat
		2. Unsuitable flow
		3. Unsuitable physical habitat
		4. Allee effect
	Fishing Creek	1. Beaver alteration of habitat
		2. Unsuitable flow
		3. Unsuitable physical habitat
		4. Allee effect
	Little Fishing (Upper Tar River, Little Fishing Creek, and Reedy Creek)	1. Beaver alteration of habitat
		2. Unsuitable flow
		3. Unsuitable physical habitat
		4. Allee effect
	Rocky Swamp	1. Beaver alteration of habitat
		2. Unsuitable flow
		3. Unsuitable physical habitat
		4. Allee effect
	Upper Tar River including Cub and Shelton Creek	1. Unsuitable flow
		2. Allee effect
		3. Unsuitable physical habitat
	Tar River	1. Unsuitable flow
		2. Allee effect
		3. Unsuitable physical habitat
	Tabbs/Ruin Creeks	1. Unsuitable physical habitat
		2. Low water quality because of contaminants
		3. Unsuitable flow
		4. Allee effect

Table 2. Strategy table showing level of implementation for management actions among 4 strategies. Status quo strategy reflects current management. The protect the best strategy focuses on management and protection of the extant populations in the Tar River basin. The expand the distribution strategy focuses on management of extant populations and establishment of new populations in the Neuse River basin. The hybrid strategy combines elements from each strategy to balance conservation between the Tar and Neuse River basins. Units describe how the level of implementation was measured (see text for additional detail). ESA = Endangered Species Act.

			Conservation strategy			
Management type	Management action	Unit	Status quo	Protect the best	Expand the distribution	Hybrid
Population management	Implement ESA section 7 and 10 regulations and influence agencies' enforcement	Effort relative to status quo	20	18.5	23	19.5
	Increase extant populations	No. juveniles released/y and location	0	3000 in Shocco Creek (Tar)	3000 in Little River and Swift Creek (Neuse)	1000 in Shocco Creek (Tar)
	Establish new populations	No. of juveniles released/y and location	0	2000 in Fishing Creek (Tar)	2000 in Deep Creek (Neuse)	4000 in Little River (Neuse)
	Use available means to protect or establish populations	Effort relative to status quo	5	9	13	5
	Manage captive populations	Yes/no	No	Yes	No	No
Habitat management	Develop best management practices for managing stream and riparian habitats	Effort relative to status quo	31	31.5	31.5	34.5
	Land acquisition and easements	Effort relative to status quo	13	16.5	14.5	15
	Restoration of in-stream and riparian habitat	Effort relative to status quo	10	8	10	9
	Maintain or restore connectivity	Effort relative to status quo and dam removal location	2	1 and Oxford dam removal	2 and no dam removals	2

Monitoring and research	Genetics monitoring and research	Effort relative to status quo	0	4	3	0
	Assessment surveys of freshwater mussel communities	Effort relative to status quo	21	21	21	21
	Targeted monitoring of extant populations	Effort relative to status quo	12	17	14.5	12
	Population viability analyses	Location of population	Swift Creek	Swift Creek	Swift Creek	Swift Creek
	Life history	Yes/No	Yes	Yes	Yes	Yes
	Propagation and stocking protocols	Status	In revision	Finalize	In revision	In revision
	Captive management research	Yes/No	No	Yes	No	No
	Assess existing and potential habitat	Effort relative to status quo	2.7	2.7	2.7	2.7
	Habitat monitoring	Effort relative to status quo	3	11	11	3
	Water quality research	Yes/No	Yes	No	Yes	Yes
Partnership building/outreach	Work with industry	Effort relative to status quo	2	2	7	2
	Work with partners	Effort relative to status quo	15	20	16.5	15

Table 3. Distributions of the number of females ≥ 3 y of age at year 20 based on population simulations. The population model was parameterized for Dwarf Wedgemussel in North Carolina (see text for details). For 10 y starting at year 2, propagated individuals raised to 3 y of age were released and assumed to survive at the same rate as extant individuals. The population started with 8 females ≥ 3 y of age and an age distribution from a stable, deterministic matrix model. The minimum, maximum, and percentiles are shown from 1000 replications.

	Number of females ≥ 3 y of age at year 20						
Number released	Minimum	5%	25%	50%	75%	95%	Maximum
250	0	4	9	15	22	38	96
500	2	11	22	33	48	79	166
1000	14	27	45	68	99	158	378
2000	16	55	94	132	192	328	743
3000	29	82	145	201	292	472	1033

The status quo strategy reflects current management, which is characterized by reacting to most recent threats and responding based on actions identified in the 5-y review (USFWS 2013) contingent on available funding. The protect the best strategy focuses on increased management and protection of the extant populations (i.e., Upper Tar and Fishing Creek watershed) in the Tar River basin. The expand the distribution strategy focuses on status quo management of extant populations in the Tar and establishment of new populations in the Neuse River basin along with increased habitat management in several watersheds in the Neuse. The hybrid strategy is a balance between the protect the best and expand the distribution strategies.

Consequences (projecting performance)

The projected performances for each strategy over a 20-y period assuming that management would be fully effective are shown in Table 4. Average values among experts were used in the multi-attribute rating technique for tradeoff analysis to identify the best performing strategy (Table 5). The effect of less-than-fully effective management was explored in the sensitivity analysis (below).

The protect the best or hybrid strategies were optimal for most of the relative values examined (Table 6). Protect the best, which focuses conservation in the Tar River basin, was optimal when all objectives were equally weighted, statewide persistence was emphasized, persistence in the Tar River basin was emphasized, or cost was moderately emphasized. The hybrid strategy was optimal when genetic diversity was emphasized. Expand the distribution strategy was optimal only when persistence in the Neuse River basin was emphasized. Status quo strategy was optimal only when cost was overwhelmingly emphasized.

Sensitivity to uncertainty in management effectiveness was examined (Fig. 3A, B). On average, elicited probabilities of management effectiveness were $P_{\mathrm{Tar}} = 0.8$ and $P_{\mathrm{Neuse}} = 0.4$ for the Tar and Neuse River basins, respectively. We examined sensitivity for $P_{\mathrm{Neuse}} \geq 0.4$ and $P_{\mathrm{Neuse}} \leq P_{\mathrm{Tar}}$. Given an emphasis on statewide persistence (see objective weights in Table 6), the protect the best strategy remained optimal regardless of uncertainty in management effectiveness (Fig. 3A). Given an emphasis on conservation, which includes increased weight on statewide persistence and genetic diversity, the hybrid strategy remained optimal (Fig. 3B). However, as the probability of management effectiveness in the Neuse decreased, the performance of the hybrid strategy declined and approached that of the protect the best strategy (Fig. 3B).

DISCUSSION

Conservation involves unavoidable tradeoffs (Burgman 2005, Bottrill et al. 2008, Joseph et al. 2008). The prominent tradeoffs in conservation of Dwarf Wedgemussel in North Carolina were: 1) conservation benefits vs management costs and 2) relative importance of persistence within Tar or Neuse River basins. Our tradeoff analyses revealed that the most promising conservation strategies focused on protecting the populations in the Tar River basin (protect the best) or balanced protection in the Tar River basin with attempts to expand the distribution in the Neuse River basin (hybrid). Continuing the status quo management was not optimal unless cost was the overriding concern. Thus, continuation of current management is almost certainly suboptimal. The strategy that allocated most effort to the Neuse (expand the distribution) was optimal only if persistence in the Neuse was emphasized over all other objectives.

The optimal strategy can depend on values from the perspective of the decision maker and stakeholders (Gregory et al. 2012b, Davies et al. 2013). Some values are codified into law, e.g., ESA, whereas others are expressions of preference and vary considerably among individual stakeholder groups. The structured decision-making process recognizes the essential role of values in decision-making

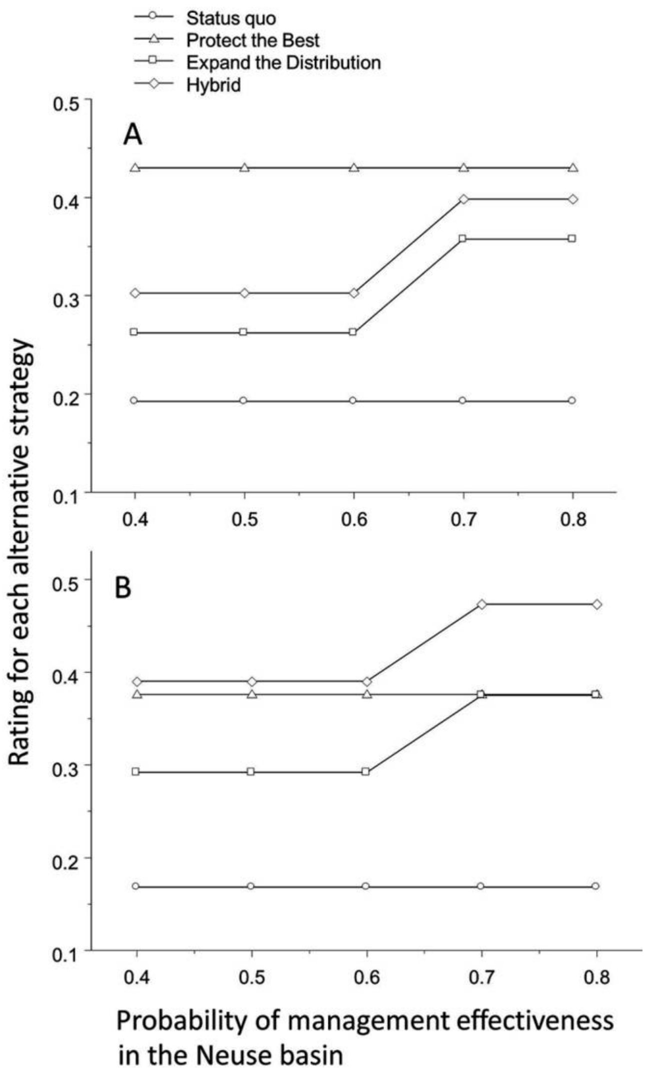

Figure 3. Comparison of strategies for conservation of Dwarf Wedgemussel in North Carolina across scenarios of management effectiveness. Probability of management effectiveness in the Tar River basin (P_{Tar}) was 0.8 in both panels. The general patterns of comparison do not change as long as management effectiveness is likely to be higher or the same in the Tar than in the Neuse River basin, $P_{\mathrm{Tar}} \geq P_{\mathrm{Neuse}}$, which was the expectation of the strategy development team. Panels differ by objective weighting from Table 6. A.—Objective weighting emphasizes statewide persistence. B.—Objective weighting emphasizes conservation by maximizing likelihood of statewide persistence and maintaining genetic diversity.

but separates subjective expressions of values from the scientific exercise of projecting performance. Impediments to finding optimal strategies can be caused by conflicting values or uncertainty in projections of performance. By deconstructing the elements of the strategic planning and being explicit about the proper roles for values and science, the source of impediments can be identified and solutions found. The structured decision-making approach has broad applicability for strategic conservation planning. The conservation strategies found to be optimal for Dwarf Wedgemussel in North Carolina would not necessarily be optimal for other mussel species in the state or for Dwarf Wedgemussel in other parts of its range. A similar decision process would have to be completed to expand beyond North Carolina or to other mussel species.

Aspects of the problem framing might differ among decision makers. For example, genetic diversity could be considered as a component of persistence rather than as a fundamental conservation objective. Holding genetic diversity as a fundamental objective was why the hybrid strategy was optimal under certain objective weightings. If viewed as a component of persistence, then the objective weighting for persistence would be spread over abundance, distribution, recruitment, and genetic diversity and the protect the best strategy would be optimal.

The comparison among strategies for Dwarf Wedgemussel was robust to uncertainty in management effectiveness, which is an important source of uncertainty (Joseph et al. 2008). Striving to reduce uncertainty is laudable, but learning is not equivalent to conservation. Research alone does not have an immediate or even necessarily a long-term conservation benefit. Conservation agencies commonly invest limited resources into research to reduce uncertainties, but not all uncertainty is an impediment to effective conservation (Runge et al. 2011, Smith et al. 2013). The choice of which uncertainty to reduce through research or adaptive management depends on whether the new information will materially improve conservation outcomes (Runge et al. 2011).

We relied on expert knowledge to project expected performance and compare strategies. Conservation planning is a forward-looking activity and, thus, requires making predictions. In the absence of specific predictive models, expert judgment and professional opinion provide the basis for projecting conservation outcomes and consequences. The structured decision-making process stipulates that expert knowledge be in a transparent and explicit form. Fortunately, best practices exist for rigorous elicitation of expert knowledge designed to ensure repeatability and guard against poor representation of expertise, anchoring, and over-confidence bias (Burgman 2005, Martin et al. 2011b, Gregory et al. 2012a, Drescher et al. 2013). The number of case studies using expert knowledge in endangered species conservation is growing in the environmental literature (Runge et al. 2011, Gregory et al. 2012a, McBride et al. 2012, Drescher et al. 2013). We followed recommended practices and interacted with most, but not all, experts on Dwarf Wedgemussel. Our intent was to receive input from a diversity of expertise and a representative sample of experts.

Uncertainty in the population model parameters could cause under- or overestimation of the required numbers

Table 4. Projected population response to strategy implementation over a 20-y period. Population attributes are abundance, occupancy, and recruitment (see text for detail). Projections were elicited from workshop participants and averages are shown.

			Current status			Alternative strategies: Status quo			Protect the best			Expand the distribution			Hybrid		
Basin	Stream reach	Historical site	Abundance	Occupied	Recruitment	Abundance	Occupied	Recruitment	Abundance	Occupied	Recruitment	Abundance	Occupied	Recruitment	Abundance	Occupied	Recruitment
Neuse River	Swift Creek (including Little and White Oak Creeks)	Yes	2	1	1	0.2	1	0.5	0.1	1	0.4	1.9	1	0.9	0.4	1	0.7
	Middle Creek	Yes	1	1	0	−1.0	0	0.0	−0.9	0	0.0	−0.9	0	0.0	−0.9	0	0.0
	Black Creek	No	0	0	0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0
	Mill Creek	No	0	0	0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0
	Neuse River	Yes	0	0	0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0
	Eno River	Yes	0	0	0	−0.1	0	0.0	−0.1	0	0.0	−0.1	0	0.0	−0.1	0	0.0
	Little River (Orange/Durham)	No	0	0	0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0
	South Flat/Flat River	No	0	0	0	0.0	0	0.0	0.0	0	0.0	0.8	1	0.5	0.0	0	0.0
	Deep Creek	No	0	0	0	0.0	0	0.0	0.0	0	0.0	2.1	1	1.0	0.0	0	0.0
	Buffalo Creek	Yes	1	1	0	−0.1	0	0.0	−0.1	0	0.0	−0.1	0	0.0	−0.1	0	0.0
	Little River (Wake/Johnston)	Yes	2	1	0	0.7	1	0.4	0.7	1	0.4	2.6	1	1.0	2.9	1	1.0
	Moccasin Creek	Yes	1	1	0	0.6	1	0.4	0.6	1	0.4	0.6	1	0.4	0.6	1	0.4
	Turkey Creek	Yes	−1	0	0	−0.2	0	0.0	−0.2	0	0.0	−0.2	0	0.0	−0.2	0	0.0
	Contentnea Creek	No	0	0	0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0
	Toisnot Swamp	No	0	0	0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0
	Nahunta Swamp	No	0	0	0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0
	Little Contentnea Creek	No	0	0	0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0

Neuse River basin			0.00	5	1	0.0	3	1.4	0.0	3	1.3	2.0	5	3.8	1.0	3	2.1
Tar River	Upper Tar River (including Cub and Shelton Creeks)	Yes	3	1	1	1.7	1	1.0	3.1	1	1.0	1.7	1	1.0	1.7	1	1.0
	Tar River	Yes	2	1	0.5	1.0	1	1.0	2.0	1	1.0	1.0	1	1.0	1.0	1	1.0
	Tabbs/Ruin Creeks	Yes	1	1	0	–1.0	0	0.0	–0.5	0	0.0	–1.0	0	0.0	–1.0	0	0.0
	Cedar Creek	Yes	0	0	0	–1.0	0	0.0	–1.0	0	0.0	–1.0	0	0.0	–1.0	0	0.0
	Fox Creek	Yes	–1	0	0	–1.0	0	0.0	–1.0	0	0.0	–1.0	0	0.0	–1.0	0	0.0
	Norris/Crooked Creeks	Yes	1	1	0	0.8	1	0.6	0.8	1	0.6	0.8	1	0.6	0.8	1	0.6
	Shocco Creek and tributaries	Yes	3	1	1	2.3	1	1.0	4.0	1	1.0	3.4	1	1.0	3.6	1	1.0
	Maple Branch	Yes	4	1	1	3.7	1	1.0	4.0	1	1.0	4.0	1	1.0	4.0	1	1.0
	Long Branch	Yes	1	1	0.5	1.2	1	1.0	2.3	1	1.0	1.2	1	0.8	1.6	1	1.0
	Upper Tar Little Fishing Creek	Yes	3	1	0	2.8	1	1.0	3.5	1	1.0	3.5	1	1.0	3.2	1	1.0
	Rocky Swamp	Yes	3	1	1	2.2	1	1.0	4.0	1	1.0	4.0	1	1.0	3.9	1	1.0
	Reedy Creek	No	0	0	0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0
	Fishing Creek	No	0	0	0	0.1	1	0.1	1.4	1	1.0	0.1	1	0.1	0.8	1	0.8
	Swift Creek	Yes	2	1	0.5	0.4	1	0.4	0.4	1	0.4	0.4	1	0.4	0.4	1	0.4
	Stony Creek	Yes	–1	0	0	–1.0	0	0.0	–1.0	0	0.0	–1.0	0	0.0	–1.0	0	0.0
Tar River basin			5.00	10	5.5	4.00	10	8.1	6.0	10	9.0	4.0	10	7.9	4.0	10	8.8

Table 5. Consequence table with performance measures to compare conservation strategies for the Dwarf Wedgemussel in North Carolina. See Methods for units for performance measures.

Objectives	Desired direction	Status quo	Protect the best	Expand the distribution	Hybrid
Abundance in Neuse	Maximize	0.0	0.0	2.0	1.0
Distribution in Neuse	Maximize	3.0	3.0	5.0	3.0
Recruitment in Neuse	Maximize	1.4	1.3	3.8	2.1
Abundance in Tar	Maximize	4.0	6.0	4.0	4.0
Distribution in Tar	Maximize	10.0	10.0	10.0	10.0
Recruitment in Tar	Maximize	8.1	9.0	7.9	8.8
Genetic diversity	Maximize	0	0	0.5	1
Public support (Neuse)	Maximize	−1	1	−1.5	−1.5
Agency costs	Minimize	2300	5900	9935	8500
Other costs	Minimize	5000	20,000	90,000	50,000

to release. However, from a risk-management perspective, we are most interested in underestimates; i.e., if we are releasing too few to be effective, how does that affect the comparison among conservation strategies? By discounting projected performance by the probability of management effectiveness, as we did in the sensitivity analysis, we examined indirectly the effect of model uncertainty. Population models have broad utility in conservation of freshwater mussels beyond the immediate task (Berg et al. 2008, Jones et al. 2012). For Dwarf Wedgemussel in North Carolina, the population model could help: 1) identify specific populations with high or low risk of persistence with or without augmentation, 2) explore the potential effect on persistence of introducing stressors that lower survival or recruitment, and 3) define expected abundance in populations for comparison with monitoring in adaptive management.

The predictions were made assuming that processes were stationary. For example, scenarios of future climate change were not considered in predicting populations because of the relatively short planning horizon and spatial scale relative to climate-change projections. However, climate change is an important source of uncertainty resulting from nonstationary processes (Conroy et al. 2011, Nichols et al. 2011), and changes in temperature and precipitation (particularly drought frequency) could affect population dynamics. Also, predation is a component of natural mortality, and predation on freshwater mussels by muskrats, otters, and raccoons has been widely reported (Neves and Odom 1989, Strayer 2008). The population model was based on the assumption that survival (1 – natural mortality) rates included a background level of predation. However, predation could change during implementation of this strategy if predators responded to increased density. Structured decision-making is an effective approach to incorporate uncertainty regarding changes in processes (Martin et al. 2011a, Gregory et al. 2013). In our example, we focused on uncertainty resulting from management effectiveness,

Table 6. Tradeoff analysis and sensitivity of optimal strategy to variation in objective weighting. The simple multi-attribute rating technique (SMART) was used to rate each strategy. Ratings under the strategy columns are the weighted average normalized scores from the consequence table shown in Table 5 using the objective weights in this table divided by 100. The rating for the optimal strategy is highlighted in bold for each objective weighting.

	Objective weights					Strategies			
Objective weighting emphasis	Persistence in the Neuse	Persistence in the Tar	Genetic diversity	Public support	Management costs	Status quo	Protect the best	Expand the distribution	Hybrid
Equal	20	20	20	20	20	0.25	**0.47**	0.30	0.38
Conservation	25	25	25	13	13	0.17	0.38	0.38	**0.43**
Persistence statewide	29	29	14	14	14	0.19	**0.43**	0.36	0.35
Persistence in the Neuse	33	17	17	17	17	0.21	0.39	**0.42**	0.36
Persistence in the Tar	17	33	17	17	17	0.22	**0.50**	0.25	0.36
Genetic diversity	17	17	33	17	17	0.21	0.39	0.33	**0.48**
Cost	17	17	17	17	33	0.38	**0.50**	0.25	0.37
Cost (extreme)	11	11	11	11	56	**0.59**	0.56	0.17	0.36

and increased predation would cause reduced effectiveness of population management. When incorporating uncertainty regardless of source, the salient question is whether altered processes would warrant a change in conservation strategy. Also, the potential for changes in underlying processes highlights the importance of monitoring during strategy implementation and periodic review of the decision structure.

Structured decision-making is scalable and can be used for project evaluation. Management actions, such as propagation, involve recurrent decisions, and the population model revealed considerable uncertainty around effectiveness of population management through these methods. Adaptive management is a subset of structured decision making for recurrent decisions (Runge 2011). Converting the conservation strategies into adaptive management plans to evaluate specific propagation and release projects would be an important next step.

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