Different management strategies are optimal for combating disease in East Texas cave versus culvert hibernating bat populations

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Abstract
Management decisions for species impacted by emerging infectious diseases are challenging when there are uncertainties in the effectiveness of management actions. Wildlife managers must balance trade-offs between mitigating the effects of the disease and the associated consequences on other aspects of the managed system. An example of this challenge is exemplified in the response to white-nose syndrome (WNS), a disease of hibernating bats. The fungal pathogen that causes WNS, *Pseudogymnoascus destructans*, continues to spread throughout North America. Texas, recently confirmed positive for the fungus, has documented 33 bat species in the state, with nearly half of those species naïve to the pathogen. We explicitly incorporated multiple management objectives, uncertainty, and risk in the Texas Parks and Wildlife Department decision to manage East Texas populations of the tri-colored bat (*Perimyotis subflavus*), a species highly susceptible to WNS. Alternatives included individual actions that act against *P. destructans* or benefit bats, a no active management option, and combinations of actions. Although our main objective was to identify WNS mitigation measures for tri-colored bats in culverts, we also considered the transferability of the decision for natural caves. In this scenario, the optimal decision differed for culverts and caves, with a “portfolio” combination of actions ranking as the best alternative for culverts and a single vaccine alternative for caves. Because the top management alternatives differed markedly between these two systems, finding treatments that have broad application is likely infeasible, given that each management decision is characterized by different mixtures of competing objectives.

Keywords
bats, proactive management, *Pseudogymnoascus destructans*, structured decision making, tri-colored bats, white-nose syndrome, WNS
Emerging infectious diseases of wildlife are difficult to manage due in part to uncertainty in the severity of impact on host populations (Plowright, Sokolow, Gorman, Daszak, & Foley, 2008). Additionally, the uncertainty in predicting the efficacy of management interventions (DeCandia, Dobson, & vonHoldt, 2018) can be complicated by trophic cascades that may occur after decline of a susceptible, common, and locally abundant species (Daszak, Cunningham, & Hyatt, 2000). Discomfort with acting in the face of uncertainty can lead resource managers to delay conservation management decisions to learn more about system dynamics, especially when undesirable outcomes may result from their actions (Meek et al., 2015). However, implementing management actions while there is still uncertainty in their efficacy may allow managers to mitigate a threat while gaining valuable data to improve future management options (Lindenmayer, Piggott, & Wintle, 2013; Runge, Rout, Spring, & Walsh, 2017). Delaying management actions to complete additional research on disease impacts or treatment effects may reduce time available for implementing proactive treatments, and reducing these uncertainties may not increase efficacy or likelihood of implementation. Furthermore, such delays may forfeit mitigation opportunities, as was the case with the sharp-snouted day frog (Taudactylus acutirostris), for which management efforts to combat chytridiomycosis were implemented too late to prevent extinction (Schloegel et al., 2006; Voyles et al., 2015).

Anticipating the arrival of an emerging infectious disease presents an opportunity to enact proactive strategies aimed at reducing the potential effect of disease before it manifests in a population. Unfortunately, appropriate opportunities for proactive management of wildlife diseases (i.e., those that do not affect humans, livestock, or crops) are rarely identified (Voyles et al., 2015), although they may be more effective and cost less than reactive approaches (Sterrett et al., 2019). A central goal in implementing proactive management is to minimize the loss of species by addressing anticipated threats (Baruch-Mordo et al., 2013; Drechsler, Eppink, & Watzold, 2011; Morrison et al., 2011). By considering actions prior to the arrival of a pathogen, managers will be primed to acknowledge constraints, identify uncertainties in the host’s ecology, and develop strategic collaborations that secure resources for improving host populations and mitigating the disease risk (Grant et al., 2017; Meek et al., 2015).

Competing management objectives and trade-offs pose additional challenges that natural resource managers must consider when managing disease in wildlife populations (Sells, Mitchell, Edwards, Gude, & Anderson, 2016). Structured decision making (SDM) is a formal, transparent, and iterative process used to solve complicated multi-objective decision problems (Keeney, 2004; Runge, Grand, & Mitchell, 2013). Within an SDM framework, managers and science experts develop the Problem statement which becomes the foundation for which management Objectives are articulated and defined. Alternatives are management strategies that are identified to achieve one or more objectives. Once objectives and alternatives are agreed upon, the manager and scientists predict the Consequences of alternatives on each objective and evaluate Trade-offs among objectives. These components comprise a “PrOACT” approach, an iterative way to facilitate insights about a decision (i.e., values focused thinking) through an SDM analysis (Hammond, Keeney, & Raiffa, 1999; Runge et al., 2013). This process has been used for a number of disease management problems, including pneumonia in bighorn sheep (Sells et al., 2016), foot-and-mouth disease in livestock (Bradbury et al., 2017), chytridiomycosis in amphibians (Canessa et al., 2018), and the identification of interventions to control outbreaks of Ebola (Li, Bj, Ferrari, Mummah, & Runge, 2017), and white-noise syndrome (WNS; Szymanski, Runge, Parkin, & Armstrong, 2009) in bats.

WNS, a disease of hibernating bats caused by the fungus Pseudogymnoascus destructans (Lorch et al., 2011; Minnis & Lindner, 2013), affects multiple hosts and has caused declines in at least seven species of hibernating bats in North America (Frick, Puechmaille, & Willis, 2016). When SDM was first applied to the management of WNS in unaffected hibernacula (Szymanski et al., 2009), the disease had only been documented in the northeastern United States (USA) for 2 years and the causative agent was not yet known. Thus, Szymanski et al. (2009) chose to focus on decisions pertaining to mitigating the spread of WNS and minimizing its impacts on bat hosts. Pseudogymnoascus destructans is now found across much of North America, and recent molecular evidence indicates the fungus is present in northern and central Texas on four species of bats (Townsend’s big-eared bat, Corynorhinus townsendii; cave bat, Myotis velifer; tricolored bat, Perimyotis subflavus; and Brazilian free-tailed bat, Tadarida brasiliensis). Texas has the highest diversity of bats of any state in the USA (TPWD, 2016) and is an important contact zone where ranges of eastern and western species overlap. Furthermore, many bat species in the state are presumed to be previously unexposed to this fungus and their vulnerability to WNS is unknown.

Based on the disease progression observed in other areas (Frick et al., 2017; Langwig et al., 2015), wildlife managers with Texas Parks and Wildlife Department (TPWD) expect WNS, and associated mortalities, within the next several years. Generally, the transition from an introduction of P. destructans to populations exhibiting signs of WNS are thought to occur within 1–5 years, with variation existing...
among species and locations (Bernard & McCracken, 2017; Frick et al., 2017; Langwig et al., 2017). This natural delay in the manifestation of the disease allows time to implement proactive management actions prior to the mass mortality characteristic of peak WNS. Individuals infected with P. destructans may show physical signs of the disease, such as white fungal growth on their wings, ears, and muzzle, as well as ulcerations and tears on wing membranes (Lorch et al., 2011; Meteyer et al., 2009). As invasion occurs, P. destructans disrupts vital physiological functions, such as water balance, cutaneous respiration, and blood circulation, leading to increased disruptions from torpor and depletion of energy reserves necessary for hibernation (Cryan et al., 2013; Verant et al., 2014; Warnecke et al., 2013; Willis, Menzies, Boyles, & Wojciechowski, 2011). Behavioral changes due to the manifestation of WNS can include cold-weather and daytime flights atypical of healthy individuals (Bernard & McCracken, 2017; Carr, Bernard, & Stiver, 2014; Turner, Reeder, & Coleman, 2011). Due to the continued devastation brought by the disease and the concerted efforts of an organized, funded national response effort, over 30 potential treatments for WNS (i.e., chemical and biological agents, and mechanical alterations that have the potential to control the growth or survival of the pathogen within hibernacula or on individual bats) are in varying stages of research and development (WNS Disease Management Working Group established under the US National WNS Response Plan, USFWS, 2011).

The tri-colored bat, a species highly susceptible to P. destructans, has suffered some of the largest declines from WNS in North America (Bernard & McCracken, 2017; Langwig et al., 2015; Frick et al., 2017; Turner et al., 2011). The small, solitary species ranges across southeastern Canada, east of the USA Great Plains, and south through eastern Mexico and Central America (Harvey, Altenbach, & Best, 2011). During winter, the species hibernates in caves, mines, and artificial roosts such as culverts (Fujita & Kunz, 1984). Upon emergence from hibernation, reproductively active females disperse across the landscape to form maternity colonies within clusters of live or dead foliage during summer. Non-reproductive females and males also disperse from hibernacula to roost singly in the leaf clusters of trees (Veilleux & Veilleux, 2004; Veilleux, Whitaker Jr., & Veilleux, 2003). Once considered one of the most widely distributed species of bat in eastern North America (Fujita & Kunz, 1984), the tri-colored bat is now absent from 69% of its hibernacula where WNS has been detected and significantly less abundant in the remainder (Frick et al., 2015). Given what we know about the species, it is reasonable to predict that currently uninfected tri-colored bats will be similarly affected by WNS once contact with P. destructans is established leading to a large decline in local populations.

We present a case study that applies principles of SDM to evaluate the consequences of management actions given the current state of knowledge about WNS for a real-world disease-mitigation decision. Our intent was to identify suitable actions for the 12 culvert hibernacula used by tri-colored bats in East Texas. We convened an SDM workshop with subject matter experts to identify a course of action to address the threat of P. destructans in susceptible populations of culvert hibernating tri-colored bats. The goals of this decision analysis were to (a) identify possible management options in human-made roost sites (e.g., culverts) to control the growth or spread of P. destructans, (b) articulate fundamental objectives (and desired outcomes) relevant to the management decision, (c) identify actions for proactive management of P. destructans and tri-colored bats within the context of this management decision, (d) predict the consequences of the proactive management actions, and (e) identify the management actions that represent the optimal decision (i.e., the best outcome) across all fundamental objectives (Hammond et al., 1999). Additionally, we analyzed whether the objectives, alternatives, and consequences identified for tri-colored bats hibernating in culverts in East Texas were transferable to WNS mitigation in natural cave ecosystems elsewhere in Texas. For this analysis, the expected outcome of the status quo scenario is based on the range of observed responses. By 2018, TPWD, with the help of Texas A&M University, identified 12 culverts in East Texas that contained colonies of hibernating tri-colored bats (ranging from 20 to 1,000 individuals per culvert; Walker, Sandel, Honeycutt, & Adams, 1996; Sandel et al., 2001) as sites for potential management actions (M. Meierhofer, Pers. Comm.). Pseudogymnascus destructans had not yet been detected in these culvert winter roost sites (i.e., the nearest detection was approximately 240 km away); therefore, TPWD recognized they have an opportunity to implement proactive management actions that could improve the survival of tri-colored bats in these human-made roosts.

2 METHODS

In March 2018, the authors met in Hadley, Massachusetts, USA to identify strategies that TPWD personnel could implement as an intervention for WNS in culverts used by tri-colored bats in East Texas. Our group was comprised of a decision-maker from TPWD (JE), subject matter experts from US Fish and Wildlife Service (USFWS; JDR, JTHC, and CJK) and Texas Tech University (NWF), and decision analysts from the US Geological Survey (EHCG) and Pennsylvania State University (RFB). Each participant was selected based on their experience in managing non-game wildlife, working with stakeholders, and direct knowledge of the WNS system.
**ProACT:** We developed a problem statement that included fundamental objectives defined by TPWD and considered a suite of alternatives (i.e., treatment and management interventions) that were documented by the WNS Disease Management Working Group. The majority of treatments for WNS are the focus of ongoing research, the results of which are largely incomplete and unpublished. For each possible action, we considered how the treatment alternative would most likely affect each management objective. Predictions were made by eliciting the effects of each alternative and its uncertainty using a four-point process to minimize overconfidence (i.e., lowest reasonable, most reasonable, highest reasonable, and confidence estimates that the true value for each alternative was within the predicted range; Speirs-Bridge et al., 2010). These predictions were informed by the latest information available for each of the individual treatments (i.e., unpublished internal reports, publications, conference abstracts and presentations, and personal communications with outside experts; Data S1).

To perform the optimization, we used a Simple Multi-Attribute Rating Technique (SMART; Hammond et al., 1999; Sells et al., 2016), which uses a “consequence table” to display predictions of how well each action performs for each of the management objectives. For the analysis, consequences were normalized across each objective (i.e., rescaled so that the outcomes are on the 0.0–1.0 scale, with 1.0 being the best outcome across the alternatives, and all other outcomes are rescaled relative to this outcome). Following the elicitation, we specified weights of importance \( w_i \) for each fundamental objective for both culverts and caves. To do this, the decision-maker and subject matter experts (“participants”) ranked the culvert objectives from 1.0 (most important) to 4.0 (least important). Participants then scored these objectives out of a possible 100 points, with the objective ranked as 1.0 receiving a score of 100, and each subsequent objective receiving a score less than or equal to the one before it, and based on the rank for each objective (Edwards & Barron, 1994; Wang, Jing, Zhang, & Zhao, 2009). Weights of importance were calculated as the proportion of the total score given to each objective \( w_i = \text{score of objective}/\text{sum of all objective scores} \) where \( \sum_{i=1}^{n} w_i = 1 \); Roszkowska, 2013). We compared weights of importance among participants and examined differences through discussion which allowed the TPWS manager to calibrate his values. For the final analysis, we used only the weights of the primary decision-maker, as he has jurisdiction for the system under consideration.

The decision-maker’s overall score for each management alternative was calculated as the sum of the normalized consequence score across each objective \( c_i^* \).

\[
\text{Overall score} = \sum_{i=1}^{n} (w_i \ast c_i^*)
\]

where the expected value for each alternative \( a_i \) is

\[
c_i^* = \frac{[a_i - a_{\text{max}}]}{a_{\text{min}} - a_{\text{max}}}
\]

where the desired outcome is to maximize the performance on an objective (e.g., minimize water contamination), and

\[
c_i^* = \frac{[a_i - a_{\text{min}}]}{a_{\text{max}} - a_{\text{min}}}
\]

where the desired outcome is to maximize the performance on an objective (e.g., maximize landowner acceptance). These sums represent an estimate of the relative support for each management alternative, accounting for trade-offs among objectives (represented by the proportional weights). The highest score identifies the best-supported alternative, or “optimal decision,” that is, an overall score of 1.0 would mean a particular alternative performed better than all other alternatives across every management objective considered. The same process was repeated to calculate normalized and weighted scores for hypothetical cave systems using the cave management objectives (Table 2).

**Expected Value of Perfect Information:** There was notable uncertainty in estimates of consequences for many of the alternatives. While imperfect knowledge of a system is inherent in any decision, only those uncertainties that would change a decision are critical to reduce. To assess how uncertainty in predicted consequences may affect the optimal decision, we calculated the expected value of perfect information (EVPI). The EVPI estimates the value (to the specific decision) of reducing an uncertainty prior to reaching a conclusion. Here, we fit a betaPERT distribution (de Glanville, Vial, Costard, Wieland, & Pfeiffer, 2014; Delignette-Muller & Rosso, 2000) to the 4-point elicited values, averaged across all participants, for the effect of each treatment alternative on two main objectives, bat persistence and cave biology. The betaPERT distribution is used for modeling expert’s estimates, incorporating the range in uncertainty specified by the most likely, minimum, and maximum estimates (Vose, 2008). The EVPI is calculated as the average outcome subtracted from the outcome of the optimal decision:

\[
\text{EVPI} = E_\theta \{ \max_d [\text{NB}(d, \theta)] \} - \max_d \{E_\theta [\text{NB}(d, \theta)]\}
\]

where \( \text{NB}(d, \theta) \) is the net benefit function for decision \( d \) and parameters \( \theta \) (Oostenbrink, Al, & Oppe, 2008). Here, a decision, \( d \), is the implementation of a treatment, and the value of \( \theta \) follows the betaPERT distribution for each treatment.
$E_{\theta}$ denotes the expectation over the full distribution of $\theta$. The expected value is the mean value of the parameter over 10,000 simulated draws from the betaPERT distribution.

### 2.1 Sensitivity analysis

In order to evaluate the robustness of the optimal decision for both culverts and caves, we performed sensitivity analyses to estimate the effects of uncertainty in the (a) weight of importance of fundamental objectives and (b) risk attitude of the decision-maker (Keeney, 2004) as follows:

1. We examined how well each alternative would perform against the status quo (i.e., do nothing beyond surveillance and monitoring) by adjusting the weight of each fundamental objective from 0.0–1.0 while holding the proportional weights of the other objectives constant. An objective's assigned weight ($w_i$) reflects the value placed on the objective by the decision-maker, relative to other objectives under consideration (i.e., the weights across all $i$ objectives sum to 1.0).

2. In order to evaluate the sensitivity of the optimal decision to the risk tolerance of the decision-maker, we used a utility function representing the decision-maker's risk tolerance to the probability of bat survival and harm to the cave environment (Goodwin & Wright, 2014). We calculated the outcome using three levels for the risk tolerance factor: 0.25, 1.0, and 4.0 (corresponding to very risk averse, risk neutral, and very risk tolerant, respectively). Utility was calculated as:

$$\text{Utility}[Pr(\text{No Extinction})] = 1 - [Pr(\text{Extinction})]^r$$

where $t$ is the number of years over which risk is predicted and $r$ is the risk tolerance factor. By considering risk explicitly, we can incorporate the decision-maker's risk tolerance into the formal decision making process for proactively managing tri-colored bat populations in both caves and culverts (Keeney, 2004; Yokota & Thompson, 2004).

### 3 RESULTS

#### 3.1 Problem statement

Substantial colonies of wintering tri-colored bats occur in East Texas, and while the known majority hibernate in culverts, some portion of the regional population also use natural cave hibernacula. Tri-colored bats are highly susceptible to WNS and wildlife managers are motivated to enact strategies to minimize the impacts of WNS in the species. Currently, researchers are developing multiple management tools to mitigate or reduce the impact of WNS. However, the effectiveness of each treatment may be site- and species-dependent and may have consequences for non-target aspects of culvert and cave systems. The decision TPWD is facing is what action(s), if any, should the agency take, within the East Texas culvert system to minimize the detrimental effects of WNS on the Texas tri-colored bat subpopulation while minimizing non-target effects.

#### 3.2 Objectives

Texas Parks and Wildlife Department identified four fundamental objectives for managing culvert-dwelling tri-colored bat populations facing the arrival of WNS in East Texas. (a) Maximize persistence of tri-colored bats, (b) minimize cost of implementing a management action, (c) minimize water contamination from a management intervention, and (d) maximize landowner acceptance of the decision. Five fundamental objectives were explicitly considered for managing cave dwelling tri-colored bat populations. (a) Maximize persistence of tri-colored bats, (b) minimize cost of implementing a management action, (c) maximize stakeholder happiness (c1. minimize water contamination, c2. maximize landowner acceptance of management decision), (d) minimize harm to cave biology (d1. minimize harm to species of greatest conservation need, d2. minimize harm to cave ecosystem function), and (e) minimize harm to cave geology. For each objective, we defined the measurable attributes used to quantify outcomes for objectives and evaluate trade-offs among competing management alternatives (Table 1).

#### 3.3 Alternatives

Following the articulation of fundamental objectives, we identified 22 management actions TPWD may be willing to implement in culverts to minimize the impacts of WNS on tri-colored bats. These actions included single treatments as well as portfolio options that involve two or more actions simultaneously or consecutively (Table 2). Actions included biological and chemical materials administered to individual bats or to the hibernacula walls, cleaning and disinfection treatments, vaccination, and altering microclimate conditions (Table 2).

#### 3.4 Evaluation of consequences for each alternative

Participants expected that failing to implement any management actions (i.e., status quo) would result in severe WNS-induced mortalities of tri-colored bats ranging from few (4% of occupied sites) to many (54% of occupied sites) based on declines at other locations within the species range. Whereas implementing a portfolio option, such as “PEG portfolio
TABLE 1  Fundamental objectives and their associated measurable attributes as determined by the Texas Parks and Wildlife Department decision-maker

| Objective | Measurable attribute                                                                 |
|-----------|--------------------------------------------------------------------------------------|
| Culvert   | 1. Maximize the probability of survival of WNS-impacted Perimyotis subflavus         |
|           | - Percent of sites with >20 individuals emerging and surviving 14 days post hibernation |
|           | 2. Minimize cost of management action                                                |
|           | - Dollars, time, and personnel; ranking: 0–10 (10 = most expensive)                  |
|           | 3. Minimize water contamination                                                      |
|           | - Invertebrate community index post-treatment; ranking: 0–5 (5 = worst impact)       |
|           | 4. Maximize landowner acceptance of treatment decision                                |
|           | - No. of cooperating landowners; ranking: 0–5 (0 = least)                            |
| Cave      | 1. Maximize the probability of survival of WNS-impacted P. subflavus                  |
|           | - Sites with >20 individuals emerging and surviving 14 days post hibernation (%)     |
|           | 2. Minimize cost of management action                                                |
|           | - Dollars, time, & personnel; ranking: 0–10 (10 = most expensive)                    |
|           | 3. Maximize stakeholder happiness                                                    |
|           |   a. Minimize water contamination                                                     |
|           |   b. Maximize landowner acceptance of treatment decision                              |
|           |   a. Invertebrate community index post-treatment; ranking: 0–5 (5 = worst impact)     |
|           |   b. No. of cooperating landowners; ranking: 0–5 (0 = least)                          |
|           | 4. Minimize harm to cave biology                                                     |
|           |   a. Ranking: 0–6 surrogate taxa harmed                                               |
|           |   b. Change in microbial function, ranking: 0–5 (5 = most change)                    |
|           | 5. Minimize harm to cave geology                                                     |
|           |   Harm expected (yes = 1, no = 0)                                                    |

Note: All other workshop participants contributed to the creation of the measurable attributes.

“PEG portfolio #2,” “vaccine,” and “steam portfolio #3” (Table 2, Table S1). “Pseudomonas,” “ClO2,” “air blow,” and “roost A/C” scored the worst among all alternatives, having the lowest score. The “status quo” ranked as low as the “Pseudomonas” alternative for the bat objective, but highest for the other objectives. On average, combinations of alternatives (i.e., portfolios) ranked higher than their individual components due to the predicted additive benefit to survival of bats (objective 1) for each action. All portfolio alternatives, except “PEG portfolio #1” and “ClO2 portfolio #1”, ranked the highest for the bat objective.

For natural cave hibernacula, where there were considerably more trade-offs among objectives, the optimal decision was “vaccine,” followed by “status quo,” “steam clean” and “chitosan” (scores ranged from 0.27 to 0.77; Table 2). In general, the alternatives that performed best for maximizing survival of bat populations at a site, performed poorly for all other cave objectives, specifically in harm to cave biology and geology (Figure 1, Table S1). This inverse relationship illustrates the strong trade-offs present in considering management options for WNS in natural cave ecosystems. Management actions taken to reduce the impact of WNS (and thus maximizing the persistence of bat populations) were expected to impose some potential negative effects to non-bat cave organisms and cave formations. The combinations of treatments that were predicted to provide added benefit to bats were also predicted to incur additional harm to cave biology and geology (Table S1).

3.5 Expected value of perfect information

The net benefit under the optimal strategy without resolving uncertainty resulted in a 0.476 probability that TPWD would continue to have sites with >20 individuals emerging and surviving 14-days post-hibernation after 5 years. If uncertainty can be completely resolved (i.e., we can gain perfect information about the effect of each of the [currently uncertain] management actions), the expected performance of the optimal management alternative to maximize the probability of survival of tri-colored bats would increase by 24.3% (i.e., resulting in a 0.629 probability of bat population persistence), by selecting “PEG portfolio #2.” When considering non-target impacts on cave fauna (cave objective four, minimize harm to cave biology), the optimal management alternative outcome, “vaccine,” decreases from 4.44 to 4.14, an improvement of 7.2% if all uncertainty were to be resolved.

3.6 Sensitivity analysis

The top four optimal decisions for culverts had little sensitivity (i.e., the optimal decision did not change) with
| #   | Alternative management strategies                                                                 | Culvert score | Cave score |
|-----|---------------------------------------------------------------------------------------------------|---------------|------------|
| 1   | Status quo: No active management/do nothing.                                                      | 0.43          | 0.69       |
| 2   | Chitosan: Spray treatment on cluster of bats during early hibernation.                            | 0.46          | 0.61       |
| 3   | VOC: Fog a site with B23 during early hibernation, with possible re-applications throughout hibernation. | 0.39          | 0.53       |
| 4   | PEG: Polyethylene glycol 8,000 applied to a site when bats are not present to disinfect or maintain low load of *Perimyotis destructans*. | 0.45          | 0.46       |
| 5   | Vaccine: The direct application of a vaccine treatment on a bat during summer/fall swarm. This method may occur orally through broadcast spray; however, bats must remain active for ~3 weeks after application in order to be effective. | 0.69          | 0.77       |
| 6   | UV early: Shine ultraviolet-C on individuals as they fly into sites (fall swarm/early hibernation) and/or substrate (pre-hibernation). | 0.37          | 0.52       |
| 7   | UV late: Shine ultraviolet-C on individuals (mid/late hibernation) and/or substrate (pre-hibernation). | 0.44          | 0.55       |
| 8   | Pseudomonas: Spray probiotic on bats at the beginning of hibernation.                            | 0.24          | 0.43       |
| 9   | Air-blow: Change microclimate by installing large fans prior to hibernation to reduce relative humidity of cave during hibernation. | 0.29          | 0.42       |
| 10  | Roost A/C: Cool microclimate 2–5°C prior to hibernation to minimize optimal growing conditions for *P. destructans*. | 0.31          | 0.43       |
| 11  | Soap and water: Clean and disinfect roost during summer with soap and water.                    | 0.41          | 0.44       |
| 12  | ClO₂: Clean and disinfect roost during summer with chlorine dioxide (ClO₂).                      | 0.29          | 0.28       |
| 13  | Steam clean: Clean and disinfect cave with pressurized steam                                    | 0.59          | 0.62       |
| 14  | Steam portfolio #1: (a) Clean and disinfect cave with pressurized steam, (b) treat roost with PEG when bats are not in the site (summer), (c) treat bats with chitosan or VOC during early-hibernation (November–December). | 0.59          | 0.42       |
| 15  | Steam portfolio #2: (a) Clean and disinfect cave with pressurized steam, (b) treat roost with PEG when bats are not in the site (summer), (c) direct application of vaccine on captured bats during summer/fall swarm. | 0.72          | 0.51       |
| 16  | Steam portfolio #3: (a) Clean and disinfect cave with pressurized steam, (b) treat roost with PEG when bats are not in the site (summer), (c) direct application of vaccine on captured bats during summer/fall swarm, (d) treat bats with chitosan or | 0.67          | 0.48       |
changing weights of the fundamental objectives \( w_i \); Figure 2). “Steam portfolio #2” remained the optimal decision when \( w_{\text{bat persistence}} \) remained between 0.57 and 0.70, \( w_{\text{cost}} \geq 0.25, w_{\text{water}} \) remained between 0.10 and 0.25, and \( w_{\text{landowner acceptance}} \geq 0.20 \). When \( w_{\text{bat persistence}} \) exceeded 0.70, the optimal decision changed to “PEG portfolio #2.”

As the value weights on water and landowner acceptance exceeded their original weights, the optimal decision switched to the “vaccine” alternative. If we reduced \( w_{\text{bat persistence}} \) below the decision-maker’s stated weight (0.57), the optimal decision switched first to the “vaccine” alternative, then to the “status quo” if less than 0.20.

The optimal decision for caves also had little sensitivity to weight on fundamental objectives (Figure 3). The “vaccine” alternative retained the highest overall support regardless of \( w_i \), especially when the estimated \( w_i \) exceeded the true \( w_i \) of each objective. The optimal decision changed from “vaccine” to “steam clean” if the proportional weight ascribed to survival of bats exceeded 0.60 \( (w_{\text{bat persistence}} > 0.60) \). When the \( w_{\text{cost}} \) exceeded 0.22, the optimal decision switched to the “status quo.”

The decision-maker’s risk profile did not alter the top alternatives for either hibernacula type, indicating that the decision framework in this first prototype was robust to variation in risk attitude.

### 4 | DISCUSSION

Deciding whether and how to implement potential management options for emerging infectious diseases of wildlife is often complex, as managers must consider multiple objectives, trade-offs, and uncertainties. A decision-maker must acknowledge areas where information is incomplete, weigh the benefits...
and opportunity costs of gathering additional information, and consider their tolerance for risk of a potentially undesirable outcome from their actions. Expending resources to reduce uncertainty through, for example, surveillance, monitoring, and research may divert resources from implementing a mitigating action (Nicol, Ward, Stratford, Joehnk, & Chadès, 2018), or sacrifice opportunities for proactive management (Grant et al., 2018; Martin et al., 2012), possibly with irreversible consequences (i.e., population collapse or extinction).

East Texas represents one of the final portions of the range where sizable winter colonies of tri-colored bats are known to exist without WNS (U.S. Fish and Wildlife Service, 2018). This system presented an opportunity to identify proactive management strategies as state wildlife managers are anticipating WNS-related impacts within the next few years. We identified treatment options that, based on available information (Data S1), were predicted to perform well across multiple objectives considered by TPWD in managing this system. None of the identified management actions are certain to reduce the impact of WNS on bats known to hibernate in culverts. However, our analysis outlines the process by which we identified a course of action that we expect will increase the odds of tri-colored bat persistence in the area while also weighing trade-offs across other objectives and acknowledging the potential to negatively affect target bat populations. By articulating the important elements to the decision problem (Bernard & Grant, 2019) facing TPWD using an SDM approach, we identified tangible treatment options that TPWD plans to implement in the culvert ecosystem prior to the emergence of WNS.

Of the combination of treatments (portfolios) considered here, few have been tested in the field. Thus, we assumed that their effects would be additive with each individual treatment in the portfolio. Although the combined effect increased a portfolio’s predicted performance for improving survival of bats, most portfolio options scored poorly for cost, water contamination, and landowner acceptance objectives. This was likely due to the assumption that effects on
these competing objectives were likewise increased with each treatment alternative; additional visits and actions at each site requires time and personnel, and landowner acceptance likely decreases with added inconvenience or disturbance from activity on their properties. We assumed that, although the quality of water in culverts in this region is normally low due to heavy transportation and agricultural runoff, certain treatments would add to impurities to the watershed. We did not explicitly consider or predict outcomes for alternatives paired with mitigation measures that would reduce these non-target effects. We theorize that careful remediation could be developed for many scenarios such that updated predictions and costs for each alternative, in subsequent decision analyses, may shift the top alternatives to include chemical treatments and portfolio options.

Importantly, the outcome of this decision analysis may not be directly transferable to other management decisions related to WNS. However, the process by which we framed objectives and predicted outcomes of alternatives enacted to benefit tri-colored bats in culverts of East Texas can be adapted for other species, roost sites, and decision makers. Many elements of this problem are shared among resource managers throughout the range of *P. destructans* and WNS (Bernard & Grant, 2019). Suitable alternatives in human-made hibernacula may not be viable options for natural cave ecosystems when considering trade-offs related to possible non-target impacts of any management action on a cave ecosystem. However, some treatment options may become feasible for application in caves if they provide increased benefits to bats while minimizing harm to cave biota, water quality, and geological features. Implementation of a treatment in cave environments is likely to require measures to avoid or mitigate potentially deleterious impacts.

Potential impacts to cave geology, cave ecosystem function, species composition, water quality, and stakeholder approval are likely to always be important components of cave management decisions. Uncertainty about these effects is therefore more likely to influence the optimal management strategy (Runge, Converse, & Lyons, 2011). While a decade of research has identified a number of potential tools to manage *P. destructans* and WNS, it is extremely difficult to test these tools against the full range of objectives that will vary among the unique ecosystems throughout the affected and at-risk areas (Bernard & Grant, 2019). It is similarly challenging to test these tools against all objectives that may be identified by diverse decision-makers. A decision-maker's

**FIGURE 2** Optimal decisions for culverts had minimal sensitivity to changing weights of the fundamental objectives ($w_i$). We varied $w_i$ for the named objective from 0.0 to 1.0 while holding the proportional $w_j$ for the other objectives constant. “Steam portfolio #2” remained the optimal decision when $w_{bat\text{ persistence}}$ remained between 0.50 and 0.70, $w_{cost} \geq 0.25$, $w_{water}$ remained between 0.10 and 0.25, and $w_{landowner\text{ acceptance}} \geq 0.20$. When $w_{bat\text{ persistence}}$ exceeded 0.70, the decision changed to “PEG portfolio #2”. As the support for water and landowner acceptance exceeded their original weights, the optimal decision switched back to the vaccine alternative. As we reduced $w_{bat\text{ persistence}}$ below the true weight (0.57), the optimal decision switches to the vaccine alternative, then to the status quo if between 0.0 and 0.20. Vertical dashed lines represent the true weight of each objective, as determined by the decision maker.
tolerance for risk in a natural system is likely to be much lower, as was the case for our comparison between caves and culverts. This difference is attributable to trade-offs in deleterious outcomes to sensitive cave ecosystems with any of the management interventions considered, and not a reflection of the value of resident bat populations differing between cave and culvert roosts. Portfolio alternatives also ranked low as an option for caves as the range of potential harm to native organisms and the natural cave environment would incur additive effects.

Ultimately, the “vaccine” alternative, as understood at the time of this analysis, was identified as an optimal management decision for tri-colored bats hibernating in caves. This conclusion resulted from a perceived ability to minimize potential non-target impacts by administering oral vaccine doses to individual bats. We recognize our desire to maximize the persistence of a single susceptible species is typically considered alongside other management objectives relevant to the short- and long-term management goals of natural resource agencies (Bernard & Grant, 2019). Thus,
future research should continue to determine how to maximize host persistence while minimizing or avoiding potential detrimental effects to ecosystems, such as (a) understanding non-target impacts of treatment options, (b) determining how disturbance from administering WNS interventions may affect individual fitness and survival, and (c) identifying whether there are control options outside of the hibernation period, and how mid-winter movements or seasonal migration may affect the predicted outcomes and optimal decision. In order to answer these remaining uncertainties, managers may consider implementing a formal adaptive management framework (e.g., Gerber & Kendall, 2018).

Our application of SDM illustrates its potential for helping address decision-making challenges related to wildlife disease. While the optimal decision we identified for sites in East Texas may not be transferrable to other sites, the SDM approach we used can be adapted to solve landscape level and cross-jurisdictional decision problems. We emphasize that an optimal strategy may vary by both specific decision contexts and decision-makers. The framework for this decision can be used for other management agencies facing WNS, as well as other emerging infectious diseases of wildlife (e.g., salamander chytridiomycosis, Martel et al., 2013). As wildlife populations continue to decline due to the increase in stressors such as habitat alteration (Didham, Tylianakis, Gemmell, Rand, & Ewers, 2007), climate change (Moritz & Agudo, 2013), and emerging infectious diseases (Jones et al., 2008), natural resource managers will continue to be challenged to make management decisions despite ever increasing uncertainty. Having access to tools that address the inherent uncertainties in wildlife decision problems using a transparent and defensible process, as provided by our application of SDM, is necessary for conserving species of concern into the 21st century.

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AUTHORS’ CONTRIBUTIONS

R.F.B. performed all analyses and led the writing of the manuscript. All authors contributed to the writing and editing of the manuscript and approved the final version.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA ACCESSIBILITY

All data used are accessible in the manuscripts’ supplemental documents.

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SUPPORTING INFORMATION

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