Using decision analysis to support proactive management of emerging infectious wildlife diseases


Despite calls for improved responses to emerging infectious diseases in wildlife, management is seldom considered until a disease has been detected in affected populations. Reactive approaches may limit the potential for control and increase total response costs. An alternative, proactive management framework can identify immediate actions that reduce future impacts even before a disease is detected, and plan subsequent actions that are conditional on disease emergence. We identify four main obstacles to developing proactive management strategies for the newly discovered salamander pathogen Batrachochytrium salamandrivorans (Bsal). Given that uncertainty is a hallmark of wildlife disease management and that associated decisions are often complicated by multiple competing objectives, we advocate using decision analysis to create and evaluate trade-offs between proactive (pre-emergence) and reactive (post-emergence) management options. Policy makers and natural resource agency personnel can apply principles from decision analysis to improve strategies for countering emerging infectious diseases.

Because pathogens are recognized as an increasing threat to biodiversity (Daszak et al. 2000), the selection and application of disease mitigation and control actions must be improved. Since 2000, there have been multiple calls for better surveillance, international coordination, and responses to emerging wildlife diseases (Kuiken et al. 2002; Grogan et al. 2014; Voyles et al. 2014), and the capacity for researchers and management agencies to identify mitigation actions has increased substantially. For example, the first conservation plans for the fungal pathogen Batrachochytrium dendrobatidis (Bd) were developed in 2005 and 2006 in Australia and the US, respectively, nearly a decade after Bd was identified as the cause of substantial amphibian population declines and extinctions (Berger et al. 1998). In contrast, a response plan for the fungal pathogen Pseudogymnoascus destructans (Pd) was drafted in 2010, just 2 years after the pathogen was identified as the cause of white nose syndrome (Voyles et al. 2014). Despite this improvement, such plans still emphasize reactive responses, with management considered only after the occurrence of the disease has been documented in wild populations. This post-hoc “crisis management” strategy is typical in wildlife disease outbreaks (Voyles et al. 2014) and conservation decision making in general (Lindenmayer et al. 2013). An alternative, more proactive approach is increasingly recognized as potentially beneficial for management of human diseases (Machalaba and Karesh 2015) and can also benefit wildlife conservation (Hyatt et al. 2015). By evaluating the range of actions that could be taken in advance of a hypothetical disease introduction, managers can minimize the
risk of reacting irrationally and ineffectively (Wilson 2008). Past experience with human and livestock diseases and invasive species demonstrates that acting prior to emergence can improve outcomes, and may also reduce costs and promote greater efficiency (Fraser et al. 2004). The key to successful implementation of such an approach is the ability to make predictions (for example, based on systematics: Brooks and Hoberg 2006) and to carry out adequate surveillance (Machalaba and Karesh 2015).

Batrachochytrium salamandrivorans (Bsal) is a fungal pathogen that has recently emerged in Europe (Martel et al. 2013, 2014), causing widespread mortality in wild and captive salamanders on that continent. Bsal can be transmitted through contact with infected individuals or substrates, causing skin lesions in infected animals; these may result in secondary bacterial infections that lead to mortality (Martel et al. 2013). The pathogen is presumably native to Asia (Martel et al. 2014) and was likely introduced into European salamander communities via the pet trade (Cunningham et al. 2015), which accordingly poses risks to salamander communities worldwide. The eastern US contains the highest diversity of salamanders in the world, including 141 species of the Plethodontidae, a family that is also potentially susceptible to Bsal (Martel et al. 2014). Although Bsal is not yet present in wild populations of salamanders in North America, Martel et al. (2014) demonstrated lethality to native US species (Figure 1). If introduced and spread throughout the US, Bsal may have devastating consequences for native North American salamanders – similar to the amphibian declines caused by the closely related Bd pathogen (eg Berger et al. 1998).

Over 28 million amphibians were imported into the US over the past decade, including an estimated average of 426 potentially infectious salamanders imported into the US each day (Richgels et al. 2016). Legislation regarding importation restrictions was being drafted by the US Fish and Wildlife Service (USFWS) prior to June 2015, an action also taken by European Union nations (Recommendation 176 on the prevention and control of the Batrachochytrium salamandrivorans chytrid fungus; 35th meeting of the Standing Committee of the Convention on the Conservation of European Wildlife and Natural Habitats; 1–4 Dec 2015). Finalized in the US in January 2016 (18 USC 42 §16.14; Interim ruling: injurious wildlife species; listing salamanders due to risk of salamander chytrid fungus), the USFWS rule lists 201 species of salamanders as “injurious” to the wildlife or wildlife resources of the US under the Lacey Act. To control the introduction and spread of an injurious species, the Lacey Act prohibits the importation and interstate transport of listed species without a permit issued by the USFWS. While preventing disease introduction during the pre-emergence stage is likely the most effective action (Mack et al. 2000), this rule, which bans imports and restricts interstate transport of amphibians, may not fully mitigate the risk to native US salamander populations. Because prevention may not be possible, we considered choices that may arise if prevention is unsuccessful. Moreover, there is a cost to delaying importation restrictions when pathogens are known to be spread via international trade (Yap et al. 2015). It is therefore also prudent to consider the cost of delaying other pre-emergence strategies that may improve population resistance or resilience to the introduction of a pathogen (Drechsler et al. 2011; Martin et al. 2012).

The optimal allocation of resources to prevention, control, or mitigation strategies depends on the current infection status of a site, the near-term potential for infection, and the range of predicted impacts (Leung et al. 2005). Given that Bsal presents a serious threat to worldwide salamander biodiversity (Martel et al. 2013) and North American salamanders are at elevated risk of infection (Yap et al. 2015; Richgels et al. 2016), decision makers and researchers have a unique opportunity to develop and implement preventative management strategies, and to devise a plan for responsive, post-emergence actions in advance of a wildlife pathogen introduction. Here, we used tools from decision analysis to enhance the capacity of scientists and resource managers at multiple organizational levels to frame decisions, identify critical information and policy gaps, effectively coordinate actions and information sharing, and identify impediments that must be overcome for a successful response to Bsal.

**Confronting emerging wildlife diseases**

Decision analysis originated in business and economics as a normative (structured) process for rational decision making, and has proven particularly useful for problems involving multiple objectives and uncertainties (Keeney and Raiffa 1993). The decision analysis framework compartmentalizes problems into five steps so as to identify and reduce impediments to finding solutions: (1) framing...
the context of the decision, (2) identifying objectives, (3) identifying actions that help to achieve objectives, (4) predicting the range of consequences of each action in terms of the objectives, and (5) evaluating trade-offs among objectives to identify optimal actions (Gregory et al. 2012). A range of facilitation techniques from behavioral decision theory can reduce various sources of bias, and counteract perceived constraints to find the best management strategy. Furthermore, decision analysis involves a range of analytical tools that allow decision makers to investigate the role of additional information in current and future decision making. When information is unavailable, formalized methods can be used to elicit expert judgments and identify key research priorities to aid future decision making. Importantly, decision analysis has already been recognized as a key framework for proactive management of wildlife disease risks (Cox et al. 2013; Mitchell et al. 2013).

In a workshop setting, we used this approach to begin to frame and explore impediments to making decisions about Bsal. Workshop participants included scientific experts (in fungal pathogen ecology, epidemiology, disease modeling, amphibian life history, and individual- and population-level responses to disease) as well as resource managers (responsible for local and regional management of amphibian populations and habitats) and policy makers (familiar with US federal and state policies on importation, biosecurity, and the pet trade). Participants were selected to represent a diversity of experience and had some responsibility for informing and carrying out management strategies, enhancing collaborative management, creating links between researchers and managers, sharing and synthesizing expert knowledge, and exploring proactive management strategies.

## Challenges for response development

We identified four major challenges to effectively developing and implementing management strategies to prevent Bsal from affecting US salamander populations, using knowledge gained from US and international responses to recent infectious wildlife diseases (eg Bd-induced chytridiomycosis in anurans, Bsal-induced die-offs of salamanders in the Netherlands, white nose syndrome in bats, and devil facial tumor disease in Tasmanian devils). The first is a lack of clear, formal legislative and organizational governance to address emerging wildlife diseases, which effectively limits the range of potential actions that can be considered during pre-emergence to mitigate post-emergence impacts. While regulatory agencies actively protect the US from human pathogens (ie the Centers for Disease Control and Prevention) and agricultural threats (ie the US Department of Agriculture), federal laws aimed at protecting amphibians are limited to the Endangered Species Act (ESA) of 1973 (which also provides implementation of CITES), the Sikes Act of 1960, and the Lacey Act (16 USC §§3371–78). Additionally, ESA applies to 18 species (9%) of salamanders but cannot be used to protect species from potential future risks such as Bsal; likewise, the Sikes Act applies only to military lands, which are managed in cooperation with the USFWS and state-level fish and wildlife agencies to ensure ecosystem protection, and covers amphibians as components thereof. The Lacey Act pertains mainly to vertebrate wildlife species (and some invertebrate taxa such as crustaceans and mollusks) that have been determined to be injurious, rather than to wildlife pathogens (eg fungi, bacteria, or viruses). While the Lacey Act is one potential regulatory mechanism to restrict trade in potentially infected salamanders, it cannot be used to restrict hosts of pathogens if the host is not determined to be injurious. New legislation would be needed to address emerging infectious diseases that may harm the health of wildlife populations but that do not have any links either to the health of agricultural animals or to human health, which are covered under existing legislation.

The second challenge involves the responsibility for managing salamander species and populations in the US, which is fragmented among agencies that have a diverse and often limited range of authority to apply management actions (Figure 2). Federal agencies manage less than one-third of the total US land area (Gorte et al. 2012) and although several agencies manage millions of hectares containing a large diversity of salamanders, most responsibility for susceptible species falls to US states. States often frame and make decisions about species conservation and management independently. The ability for managers to rapidly coordinate and communicate current and planned actions across organizations and regions was considered a critical obstacle to mitigating the risk of Bsal. Overcoming this impediment is particularly important when decisions made by one agency influence another’s ability to successfully implement a management policy. Using tools from decision analysis, natural resource managers can link their actions across space and time. Understanding the full range of problems associated with making decisions about Bsal across states and agencies can provide insights into which require joint allocation, in circumstances where one decision and outcome will influence another. Additionally, opportunities for learning across agencies with similar decision-making problems can be framed within a formalized adaptive management framework (Williams et al. 2009).

The third challenge, often overlooked but critically important, is that even if optimal strategies for disease management are identified, they may conflict with an agency’s other ecological, social, or economic objectives. Natural resource agency personnel and policy makers have articulated a range of fundamental objectives for mitigating hazards associated with Bsal (Table 1). These objectives include aspects of salamander conservation, such as population persistence and diversity, and aspects of Bsal
risk mitigation, such as its presence and impact on populations. However, other (possibly conflicting) objectives relate to social benefits (e.g., recreation opportunities on managed lands and public use of habitats shared by salamanders); economic concerns, including ecosystem services, management costs, and costs to stakeholders (i.e., those in the amphibian pet trade); and values pertaining to other wildlife taxa (e.g., non-salamander species of concern).

While some management actions (Table 2) may be effective at reducing or eliminating Bsal risk prior to first detection, natural resource agencies may still be hesitant to implement these strategies if they are perceived to affect other objectives, such as detracting from recreational opportunities or harming other species. Structuring a decision analysis involves identifying objectives relevant to each decision maker, and allows proposed management solutions to be measured against the entire set of objectives. Because they likely depend on the relative importance of each objective, trade-offs can be identified through this type of assessment. Using this approach prior to Bsal detection can help natural resource agencies prepare for difficult decisions (i.e., trade-offs) or employ strategies for minimizing the consequences for other objectives. Different agencies may also have non-overlapping objectives and may implement actions at different spatial scales (from continental to local). Such competing interests can make it harder to identify a single solution for effective Bsal management, and therefore highlights the need for linked and context-dependent decision analysis to evaluate a complex set of potential management strategies.

A fourth challenge may remain even after those described above have been mitigated: there may be few options for management. Uncertainties in the ecology of a pathogen may contribute to a lack of viable solutions available in advance of a disease outbreak (Woodhams et al. 2011). As uncertainty is a hallmark of emerging infectious disease management, or indeed of any resource management problem, we devote more attention below to the framework for developing and selecting management actions in the face of uncertainty.

| Table 1. Three examples of competing objectives in Bsal management among US agencies |
|-----------------------------------------------|-----------------------------------------------|
| Agency | Objective 1 | Objective 2 |
| US Fish and Wildlife Service | Minimize substantial economic impact to individuals related to changes in salamander imports and pet trade policy | Restrict international trade and interstate movement of salamanders to mitigate risk of importation of Bsal |
| US Department of Defense | Conservation of salamander populations (minimize need for listing salamander species under the Endangered Species Act [ESA]) | Maintain ability to conduct military training and mission-critical operations |
| US National Park Service | Conservation of salamander populations (including those listed under the ESA) | Maintain natural ecosystem processes |

Figure 2. Fragmented management responsibility for salamander populations in the US complicates the coordination of management decisions; state and federal agencies may share jurisdiction for areas characterized by high salamander diversity, and also must consider other objectives that are locally important but may compete with any Bsal management response. Here, we overlay county-level salamander diversity (top right; occurrence of 1–30 salamander species) with federal land ownership (bottom left), resulting in a small and fragmented federal jurisdiction over management decisions for salamander diversity (indicated by numbers of species present on individual protected lands: usfs = US Forest Service; nps = National Park Service; fws = US Fish and Wildlife Service; blm = Bureau of Land Management) across the US; most management decisions for salamander populations are the responsibility of state agencies.
Developing management strategies despite uncertainty

Disease management requires acting with imperfect information. Deliberately including uncertainties into the evaluation of alternative strategies can greatly improve the identification of robust alternatives (Regan et al. 2005). We framed decisions within a conceptual model of disease emergence and impacts on salamander populations. By using this model, we were able to characterize the uncertainties expected to influence the successful implementation of a variety of potential proactive management strategies. The resulting influence diagram considered two immediately salient and potentially competing objectives of the USFWS (persistence of salamanders and economic costs; Figure 3). The diagram included four operational steps for disease emergence: pre-emergence, emergence, epidemic, and establishment, as in Langwig et al. (2015). Researchers and managers jointly built an influence diagram for each stage of Bsal emergence to capture the factors that influence salamander population responses to the disease. Management actions that influenced each factor were then added as an example of how management strategies (which could consist of simultaneous or coordinated actions) could be developed and formally evaluated. Potential actions were generated and separated into general categories of actions and stage of emergence where the action would be appropriate (Table 2) based on experiences across agent types, affected taxa, and environmental conditions. The relative effectiveness of each action and the experts’ confidence in the efficacy of each action was formally elicited.

However, these actions are context-specific and do not necessarily represent the best action in every situation. To help devise innovative actions relevant to various management contexts, we used formal elicitation methods that identified research needs at population, community, and habitat scales. These included: (1) developing additional diagnostic and detection methods for Bsal (e.g., in environmental samples); (2) assessing the susceptibility of additional potential hosts, including vertebrates other than salamanders; (3) identifying the transmission pathways to focus control efforts; (4) developing and evaluating the effectiveness of short-term containment measures (such as site isolation and local treatment); and (5) long-term strategies to promote host-pathogen coexistence (such as breeding for resistance or tolerance).

Experts at the workshop also recognized that a single action will most likely not be effective in managing Bsal...
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and its effects on populations, and that, ultimately, response strategies are more likely to represent combinations of actions, depending on the decision context and its constraints. For example, we used a simplified “Bayesian belief network” (BBN; Marcot et al. 2006), a tool from decision analysis, to formalize how the impact of Bsal emergence is conditional on the probability of spread, which in turn is conditional on the probability of entry (Figure 4). Specific management actions may be aimed at modifying those probabilities. In this example, regulating trade can change the probability of entry, and therefore the probability of spread, whereas containment efforts may change the probability of spread without affecting entry. Expanding this BBN will allow us to explicitly identify and characterize these linked decisions. Graphical decision aids, such as influence diagrams and BBNs, can be scaled to reflect the different actions available to management agencies, relevant uncertainties and hypotheses, diverse management objectives, and the spatial (local, state, region) and temporal (short-, medium-, long-term) dimensions of disease management responses.

Optimal management strategies may change as uncertainties are reduced through monitoring and/or research, which should target the uncertainties that most affect the choice of preferred management actions. Reducing uncertainty increases the ability to predict and attain desired outcomes (Runge et al. 2011). Moreover, actions are likely to be initiated at different stages of disease emergence (Langwig et al. 2015). Stages may be imperfectly observed but may be identified, for example, by the first detection of the pathogen (at a continental or local scale), or by the first detection of population declines or die-offs. Information about the state of the system (ie gathered by surveillance) is therefore vital and should be clearly linked to management actions and objectives so that it is used as efficiently as possible (Lyons et al. 2008).

Conclusions

With the advance knowledge of the threat posed by Bsal to US salamander species, scientists have a unique opportunity to address the introduction, spread, effects, and control strategies for a novel infectious disease before widespread declines occur. Decision analysis offers a wide range of tools that can address the challenges that are identified within an explicit and transparent framework (Keeney and Raiffa 1993). Specific management problems were not evaluated during this workshop. However, natural resource agencies and policy makers will be able to employ the principles of decision analysis and build on the range of objectives, conceptual models, and uncertainties identified in order to facilitate the framing of Bsal decision problems and to explore proactive management strategies. The opportunity to actively manage populations ahead of epidemics is a notable hallmark of the Bsal threat, which may serve as an example in developing responses to future emerging infectious diseases. Evaluating and implementing strategies for Bsal and other emerging infectious wildlife diseases may require new approaches, since proactive management of populations and habitats (which might result in suboptimal outcomes at present) seeks to mitigate a disease threat that has not yet emerged. This differs from the “dual control” problem in adaptive management where managers choose strategies to optimize outcomes both now and in the future (eg by learning about system controls; Walters and Hilborn 1978). Given the degree of uncertainty that characterizes management of emerging infectious diseases, using a formal adaptive management framework may also be desirable, because it could provide insights into mitigating local disease risk while also maximizing
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**Figure 4.** Simplified example of an influence diagram (Bayesian belief network) to guide the choice of Bsal management actions in the US. The outcome (impact) is conditional on stochastic events such as the entry and spread of the pathogen. Both are represented as conditional probability tables, where probabilities may or may not be influenced by management actions. This influence diagram may be easily expanded to account for more complex scenarios (e.g., multiple sources of entry and additional control options).

the opportunity to learn about the disease and improve future management (Williams et al. 2009).

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**References**


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