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Concepts and Questions

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

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Running title:
EH Campbell Grant *et al.*
Proactive wildlife disease management

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.

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In a nutshell:

- Effective management of emerging infectious disease is characterized by a need for rapid response in the face of uncertainty
- Exploring, developing, and implementing proactive management strategies (prior to emergence) can be aided using principles from decision analysis
- We identify four challenges to successful proactive management for the salamander chytrid fungus *Bsal*, including a lack of disease policy, fragmented management responsibility, multiple competing objectives, and few effective options for post-emergence control
- Proactive management for emerging diseases requires innovation, confronting perceived constraints, and collaboration to ensure that resources spent on research, monitoring, and surveillance are directly linked back to improving wildlife populations

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 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 (eg recreation opportunities on managed lands and public use of habitats shared by salamanders); economic concerns, including ecosystem services, management costs, and costs to stakeholders (ie those in the amphibian pet trade); and values pertaining to other wildlife taxa (eg 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 (ie 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.

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

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References

Berger L, Speare R, Daszak P, *et al*. 1998. Chytridiomycosis causes amphibian mortality associated with population declines in the rain forests of Australia and Central America. *P Natl Acad Sci USA* **95**: 9031–36.

Brooks DR and Hoberg EP. 2006. Systematics and emerging infectious diseases: from management to solution. *J Parasitol* **92**: 426–29.

Cox R, Sanchez J, and Revie CW. 2013. Multi-criteria decision analysis tools for prioritising emerging or re-emerging infectious diseases associated with climate change in Canada. *PLoS ONE* **8**: e68338.

Cunningham AA, Beckman K, Perkins M, *et al*. 2015. Emerging disease in UK amphibians. *Vet Rec* **176**: 468.

Daszak P, Cunningham AA, and Hyatt AD. 2000. Emerging infectious diseases of wildlife-threats to biodiversity and human health. *Science* **287**: 443–49.

Drechsler M, Eppink FV, and Wätzold F. 2011. Does proactive biodiversity conservation save costs? *Biodivers Conserv* **20**: 1045–55.

Fraser C, Riley S, Anderson RM, and Ferguson NM. 2004. Factors that make an infectious disease outbreak controllable. *P Natl Acad Sci USA* **101**: 6146–51.

Gorte RW, Vincent CH, Hanson LA, and Rosenblum MR. 2012. Federal land ownership: overview and data. Washington, DC: Congressional Research Service. CRS Report R42346.

Gregory R, Failing L, Harstone M, *et al*. 2012. Structured decision making: a practical guide to environmental management choices. Chichester, UK, and Hoboken, NJ: Wiley-Blackwell.

Grogan LF, Berger L, Rose K, *et al*. 2014. Surveillance for emerging biodiversity diseases of wildlife. *PLoS Pathog* **10**: e1004015.

Hyatt A, Alonso Aguirre A, Jeggo M, and Woods R. 2015. Effective coordination and management of emerging infectious diseases in wildlife populations. *Ecohealth* **12**: 408–411.

Keeney RL and Raiffa H. 1993. Decisions with multiple objectives: preferences and value trade-offs. Cambridge, UK: Cambridge University Press.

Kuiken T, Leighton F, Fouchier R, *et al*. 2002. Pathogen surveillance in animals. *Science* **309**: 1680–81.

Langwig KE, Voyles J, Wilber MQ, *et al*. 2015. Context-dependent conservation responses to emerging wildlife diseases. *Front Ecol Environ* **13**: 195–202.

Leung B, Finnoff D, Shogren JF, and Lodge D. 2005. Managing invasive species: rules of thumb for rapid assessment. *Ecol Econ* **55**: 24–36.

Lindenmayer DB, Piggott MP, and Wintle BA. 2013. Counting the books while the library burns: why conservation monitoring programs need a plan for action. *Front Ecol Environ* **11**: 549–55.

Lyons JE, Runge MC, Laskowski HP, and Kendall WL. 2008. Monitoring in the context of structured decision-making and adaptive management. *J Wildl Manage* **72**: 1683–92.

Machalaba C and Karesh WB. 2015. Envisioning a world without emerging disease outbreaks. *Solutions* **6**: 63–71.

Mack RN, Simberloff D, Lonsdale WM, *et al*. 2000. Biotic invasions: causes, epidemiology, global consequences, and control. *Ecol Appl* **10**: 689–710.

Marcot BG, Steventon JD, Sutherland GD, and McCann RK. 2006. Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. *Can J Forest Res* **36**: 3063–74.

Martel A, Blooi M, Adriaensen C, *et al*. 2014. Recent introduction of a chytrid fungus endangers Western Palearctic salamanders. *Science* **346**: 630–31.

Martel A, Spitzen-van der Sluijs A, Blooi M, *et al*. 2013. *Batrachochytrium salamandrivorans* sp nov causes lethal chytridiomycosis in amphibians. *P Natl Acad Sci USA* **110**: 15325–29.

Martin TG, Nally S, Burbidge A, *et al*. 2012. Acting fast helps avoid extinction. *Conserv Lett* **5**: 274–80.

Mitchell MS, Gude A, Anderson NJ, *et al*. 2013. Using structured decision making to manage disease risk for Montana wildlife. *Wildlife Soc B* **37**: 107–14.

Regan HM, Ben-Haim Y, Langford B, *et al*. 2005. Robust decision-making under severe uncertainty for conservation management. *Ecol Appl* **15**: 1471–77.

Richgels KLD, Russell RE, Adams MJ, *et al*. 2016. Spatial variation in risk and consequence of *Batrachochytrium salamandrivorans* introduction in the USA. *R Soc Open Sci*; doi:10.1098/rsos.150616.

Runge MC, Converse SJ, and Lyons JE. 2011. Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program. *Biol Conserv* **144**: 1214–23.

Voyles J, Kilpatrick AM, Collins JP, *et al*. 2014. Moving beyond too little, too late: managing emerging infectious diseases in wild populations requires international policy and partnerships. *Ecohealth* **2014**: 1–4.

Walters CJ and Hilborn R. 1978. Ecological optimization and adaptive management. *Ann Rev Ecol Syst* **9**: 157–88.

Williams BK, Szaro R, and Shapiro C. 2009. Adaptive management: the US Department of the Interior technical guide. Washington, DC: Adaptive Management Working Group, US Department of the Interior.

Wilson RS. 2008. Balancing emotion and cognition: a case for decision aiding in conservation efforts. *Conserv Biol* **22**: 1452–60.

Woodhams DC, Bosch J, Briggs CJ, *et al*. 2011. Mitigating amphibian disease: strategies to maintain wild populations and control chytridiomycosis. *Front Zool* **8**: 8.

Yap TA, Koo MS, Ambrose RF, *et al*. 2015. Averting a North American biodiversity crisis. *Science* **349**: 481–82.

Figure 1. *The eastern newt (*Notophthalmus viridescens*) is broadly distributed throughout eastern North America and is one of several species of US amphibians with demonstrated susceptibility to the* Batrachochytrium salamandrivorans *(*Bsal*) pathogen.*

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.*

Figure 3. *Simplified prototype influence diagram that links potential management actions (green rectangles) and abiotic and biotic factors affecting disease and amphibian processes (red ovals represent stochastic events, white ovals represent contributing processes) to two fundamental*

management objectives (red hexagons): persistence of salamanders and economic impacts of management actions, which are used as examples here but would be expanded to include all objectives of each local decision maker. Outcomes of a chosen set of management actions may lead to positive or negative outcomes for the objectives. For example, regulating trade may reduce profits for some segments of the pet trade but create new markets for within-state salamander trade, while anti-fungal treatments may improve the persistence outcomes for some species but not others.

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 (eg multiple sources of entry and additional control options).*

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

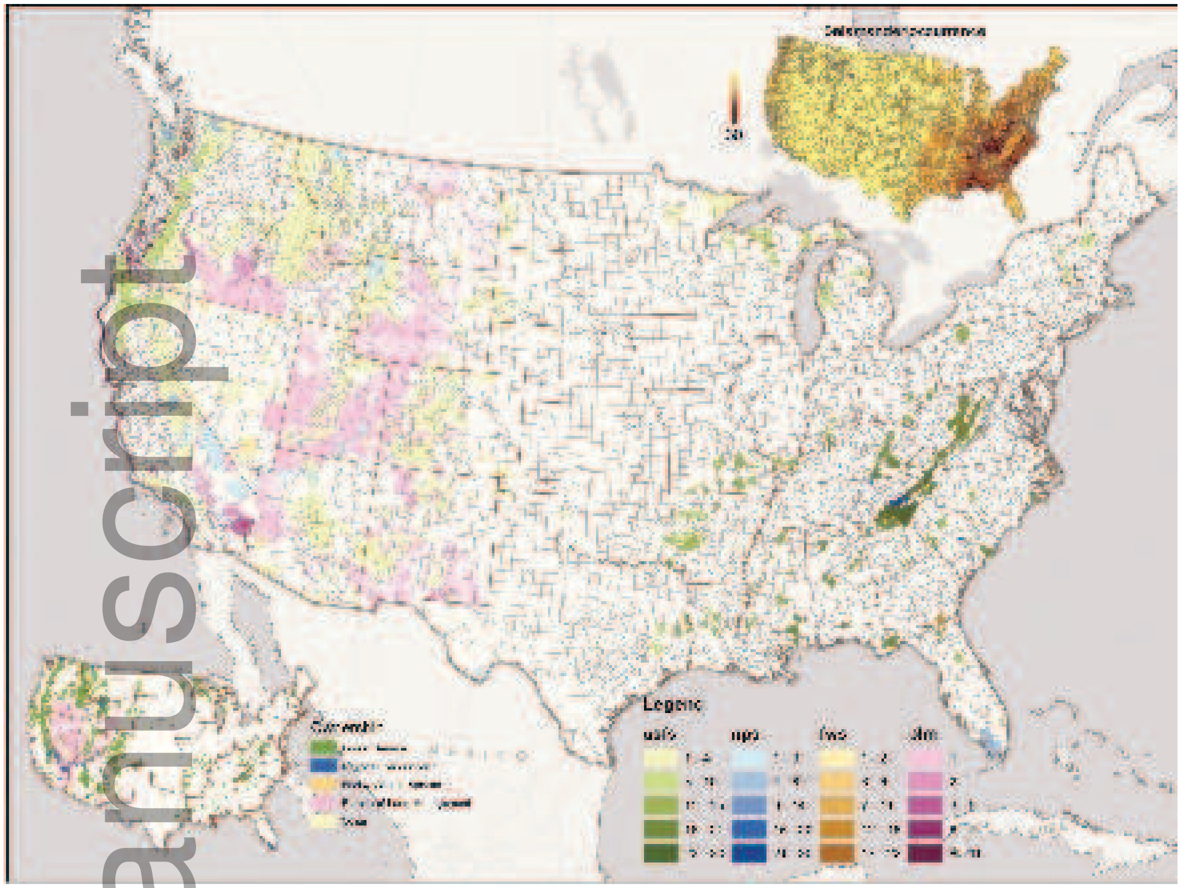
Table 2. List of potential action categories considered during each stage of pathogen emergence, with their expected level of effectiveness and confidence in that effectiveness

Potential action category	Stage of emergence				Expected relative effectiveness	Relative confidence in effectiveness
	P	E	Ep	Es		
Containment of infected sites		X	X	X	Low	Low
Alter host species composition	X	X			Low	Low
Apply anti-fungal agents to salamanders	X	X			Low	High
Remove susceptible and tolerant salamanders from infected sites	X	X			Low	High
Limit site access (by humans and other vertebrates)	X	X	X	X	Low	High
Quarantine salamanders	X	X	X		Moderate	Low
Require health certification	X	X			Moderate	Low
Apply anti-fungal agents to habitats	X	X			Moderate	Low
Vaccinate salamanders	X	X			Moderate	Low
Apply probiotics to salamanders	X	X			Moderate	Low
Physical modification of habitat	X	X	X	X	Moderate	Moderate
Enforce fieldwork biosecurity	X	X	X		Moderate	High
Create assurance colonies	X	X			Moderate	High
Breed salamanders for resistance and/or tolerance	X				High	Low
Deploy *Bsal* zoospore removal methods	X	X	X	X	High	Low
Enact legislation that authorizes actions on wildlife pathogens	X				High	Low

Ban all importation of salamanders	X	X	X		High	Moderate
Restrict salamander trade	X	X	X		High	Moderate
Destroy habitats of infected sites		X	X	X	High	Moderate

Notes: P = Pre-emergence, E = Emergence, Ep = Epidemic, and Es = Establishment. Expectations were elicited using the expert opinions of six groups of participants (each composed of approximately five individuals) during the workshop.

fee_1481_f1.jpg



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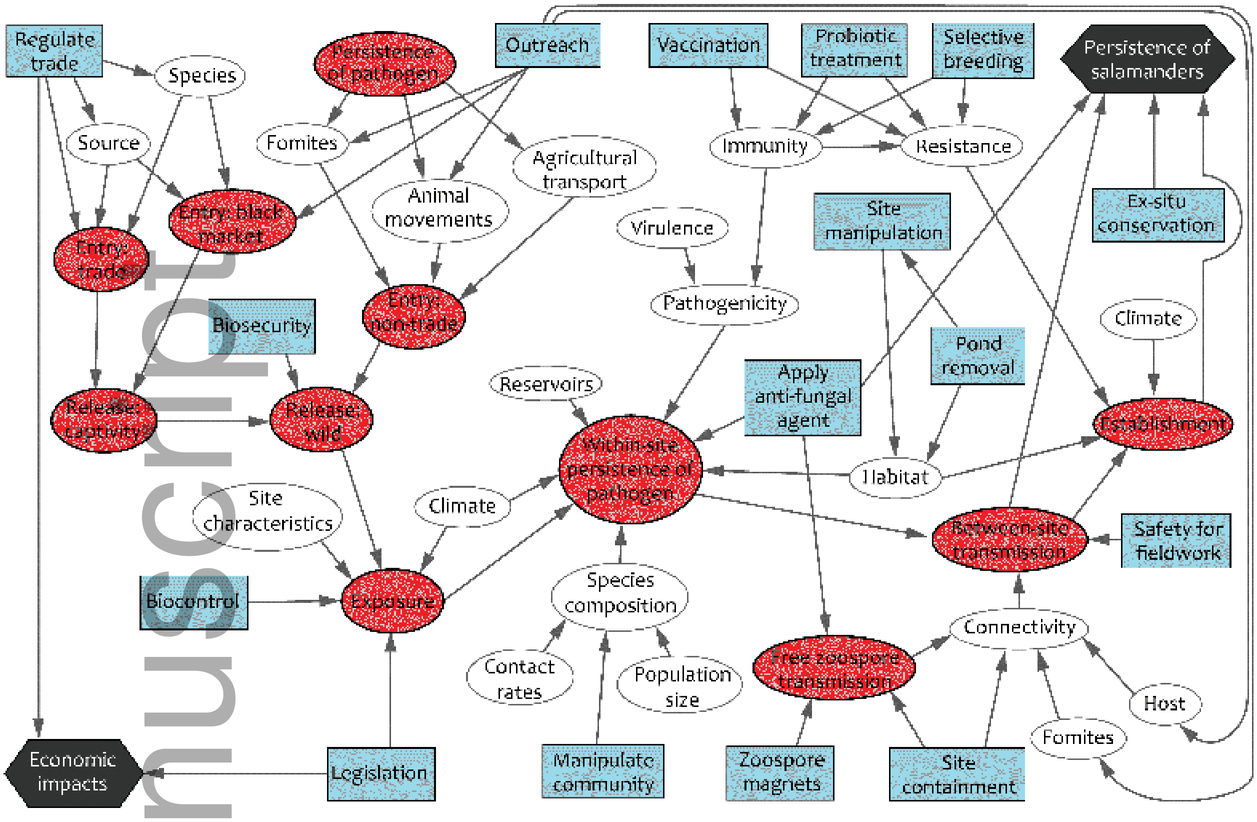

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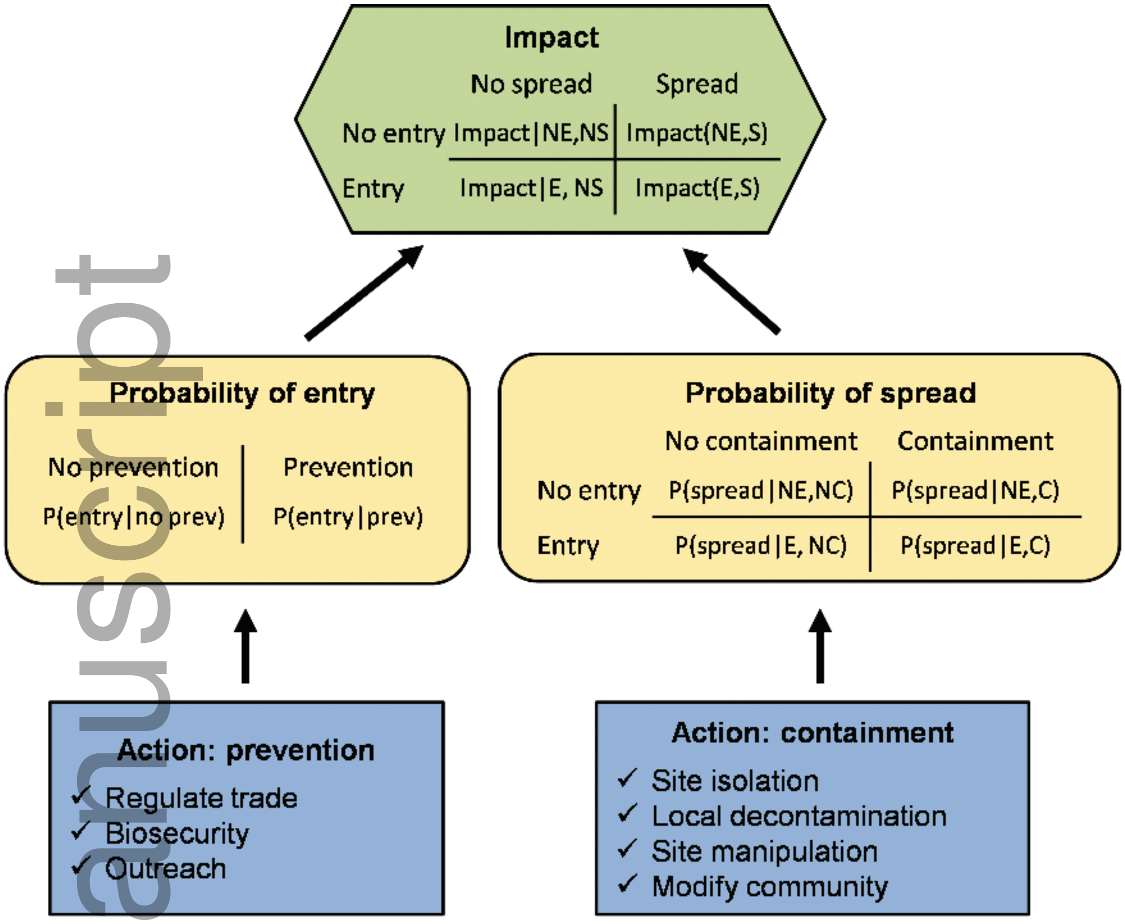

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