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Title: Living with the enemy: facilitating amphibian coexistence with disease

Authors: Ben C. Scheele[1,2], Claire N. Foster[1], David A. Hunter[3], David B. Lindenmayer[1,2], Benedikt R. Schmidt[4,5], Geoffrey W. Heard[6]

[1] Fenner School of Environment and Society, Australian National University, Canberra 2601, Australia

[2] National Environmental Science Programme, Threatened Species Recovery Hub, Australia

[3] New South Wales Office of Environment and Heritage, Albury NSW 2640, Australia

[4]Department of Evolutionary Biology and Environmental Studies, University of Zurich, Winterthurerstrasse 190, 8057, Zurich, Switzerland

[5] Info Fauna Karch, UniMail, Bâtiment G, Bellevaux 51, 2000 Neuchâtel, Switzerland

[6] School of Environmental Sciences, Charles Sturt University, Albury NSW 2640, Australia

Abstract

Globalization has facilitated the emergence and spread of novel pathogens, representing a major conservation challenge. The amphibian disease chytridiomycosis, caused by the fungal pathogen *Batrachochytrium dendrobatidis,* epitomizes this unprecedented threat, being responsible for declines and extinctions of amphibians worldwide. Chytridiomycosis has had both immediate catastrophic impacts during initial epidemics, as well as more variable, ongoing effects as the pathogen transitions to endemicity in its new distribution. Where *B. dendrobatidis* is now endemic, effective management actions are needed to prevent further extinctions of species. Yet, after nearly 20 years of research, management solutions remain rare or largely untested. Here, we highlight the potential for mitigation strategies focused on the environmental part of the host-pathogen-environment triangle to facilitate coexistence with the pathogen, using an extensive literature review to demonstrate that environmental conditions and demographic processes can strongly mediate the impact of *B. dendrobatidis*, and the capacity of amphibian populations to withstand disease-associated mortality. In particular, novel management approaches to achieve coexistence could focus on manipulating environmental conditions to decrease suitability for *B. dendrobatidis* and/or increase demographic resilience to disease-associated mortality. Such strategies include translocation to, or creation of, environmental refuges, and habitat manipulation to increase recruitment and offset elevated adult mortality. We argue that responding to chytridiomycosis requires a conceptual readjustment of our baselines to recognize that endemic *B. dendrobatidis* infection is the ‘new normal’ in surviving populations of many susceptible amphibian species. We conclude with recommendations for research and management actions that can help achieve coexistence of amphibian species susceptible to *B. dendrobatidis*.

Key words: adaptive management; amphibian conservation; *Batrachochytrium dendrobatidis*; chytrid fungus; wildlife disease

Highlights

- Chytridiomycosis continues to cause amphibian declines decades after its emergence
- Some amphibians coexist with chytridiomycosis through a diverse range of responses
- The ranges of many susceptible species have contracted to environmental refuges
- A focus on coexistence rather than eradication could improve conservation outcomes
- Environmental manipulation may facilitate coexistence with chytridiomycosis

1. Introduction

The transition of emerging infectious pathogens to endemicity can provide unique insights into the epidemiology of wildlife disease, including the various pathways through which pathogens and hosts achieve coexistence. The last century provides numerous examples of the destructive power of pathogens introduced into naïve host populations, including avian malaria in passerine birds (Samuel et al., 2015), squirrel parapoxvirus (Tompkins et al., 2002), and white nose syndrome in bats (Leopardi et al., 2015). Rightfully, the devastating effects associated with epidemics have received much attention. However, the long-term ecological, demographic, behavioural and evolutionary responses of hosts to novel pathogens are deserving of equal focus. Many pathogens that are highly destructive outside of their native range coexist with host populations within the pathogen's native range (Tompkins and Begon, 1999), suggesting that there is potential for coexistence to develop in emerging host-pathogen systems. Uncovering mechanisms that underpin coexistence is of great interest for managing wildlife pathogens, and can reveal pathways through which managers may be able to expedite host-pathogen coexistence.

The disease chytridiomycosis is a key driver of global amphibian declines (Lips, 2016). Chytridiomycosis is caused by infection with one of two fungal species, *Batrachochytrium dendrobatidis* (discovered in 1998, Berger et al., 1998; Longcore et al., 1999), and *B. salamandrivorans* (discovered in 2013, Martel et al., 2014). The global expansion of both *Batrachochytrium* pathogens – which originated in East Asia (O'Hanlon et al., 2018) – has been facilitated by humans, particularly through wildlife trade (Martel et al., 2014). *Batrachochytrium dendrobatidis* (hereafter *Bd*) is now found on all continents with amphibians, while *B. salamandrivorans* is currently invasive only in Europe, but there are major concerns about its potential introduction into the Americas (Martel et al., 2014).

Disease theory predicts that emerging single-host pathogens can either transition to endemicity, or fade out after epidemic outbreaks (Lloyd-Smith et al., 2005). In contrast, emerging multi-host pathogens are unlikely to fadeout, and can persist long-term (Lloyd-Smith et al., 2005). The classic example of a persistent multi-host pathogen in the wildlife disease literature is avian malaria (caused by the blood parasite *Plasmodium relictum*) in Hawaii. Nearly a century after initial bird declines and extinctions in the 1920s, the pathogen is now endemic and host responses range from high ongoing susceptibility to evolution of resistance with partial recovery and/or persistence in environmental refuges (Samuel et al., 2015). Similarly to avian malaria, *Bd* has a number of traits that make long term persistence of the pathogen in infected populations likely. First, *Bd* has an extremely broad host range, with infections reported in over 700 amphibian species, as well as non-amphibian hosts (Lips, 2016). Second, *Bd* can persist in both non-declining amphibian reservoir hosts (Scheele et al., 2017b) and the environment (Johnson and Speare, 2005). Finally, *Bd* appears to be able to maintain high virulence post-emergence (Voyles et al., 2018). These factors combined with the strong influence of environmental conditions on *Bd* pathogenicity (Lips, 2016), mean that species that have declined due to *Bd* epidemics have exhibited a range of trajectories, from extirpations, to ongoing declines, stabilization at lower density or even recovery (Scheele et al., 2017c).

The overarching tenet of this paper is that the environmental component of the *host-pathogen-environment* disease triangle (Scholthof, 2007) offers untapped management potential in the context of chytridiomycosis. We do not discount the importance of host-pathogen factors (namely host tolerance and resistance, vaccines or manipulation of host microbiota and evolution of reduced pathogen virulence), but these factors have received much attention elsewhere. Mitigation strategies based on the environmental part of the host-pathogen-environment triangle, on the contrary, have only recently emerged in the literature, yet could be widely applicable because environmental conditions can strongly mediate the impact of biotic threats (Scheele et al., 2017a, 2018a), and because most amphibian species are endangered by multiple threats, many of which may be managed to offset *Bd* impacts (Grant et al., 2016).

To provide a foundation for the development of mitigation strategies focused on the environmental part of the host-pathogen-environment triangle, we review the literature on the context-dependent nature of host-pathogen dynamics in amphibian species that have experienced *Bd*-associated declines. Our synthesis identifies the crucial role of environmental context in shaping infection dynamics, and how host demographic responses and population processes can facilitate coexistence. New management approaches could achieve coexistence through: (1) manipulating environmental conditions to decrease the pathogenicity and/or virulence of *Bd*, or (2) bolstering population resilience to disease-induced mortality by facilitating compensatory mechanisms such as increased recruitment success and consistency, and/or reduced mortality from other sources. In the final section of this paper, we provide research and management recommendations to guide actions that aim to secure the long-term conservation of species challenged by endemic *Bd*. We argue there is a need to update our baseline ecological knowledge of declining species to recognize that endemic *Bd* infection is the 'new normal' for many susceptible species (Mendelson et al., 2019 -This issue), and adjust our conservation and management goals accordingly. We highlight how such a shift can establish a new path for action, by refocussing on management opportunities and avoiding the inevitable failure of conservation actions that seek to eradicate *Bd* or return species to their previous state.

2. Ecological responses to endemic *Batrachochytrium dendrobatidis*

An extraordinarily broad range of mechanisms have been associated with amphibian persistence in the post-epidemic phase of *Bd* emergence, with host responses being species-specific and context dependent. Here, we describe the results of a targeted literature review of the 'ecological' (including demographic and behavioural) responses to endemic *Bd* infection among amphibian hosts and how these vary with environmental context (those interested in the role of host-immune responses and shifts in pathogen virulence in coexistence are referred to the Supplementary Material for brief overviews of both processes). We focus on susceptible amphibian species that experienced declines during initial epidemics, and for which endemic chytridiomycosis continues to be a source of host mortality. For a full list of papers consulted, see Appendix A in the Supplementary Material. We note here that the available literature is biased towards research conducted in the U.S.A., Australia and Western Europe. In each section below, we describe the processes associated with amphibian persistence with *Bd* and outline the management implications and associated opportunities.

2.1. Contraction to geographic refuges

Following the emergence of *Bd*, susceptible amphibian species may experience a contraction to geographic refuges, defined here as a proportion of a host species' range where *Bd* is absent (Fig. 1). Although not technically a mechanism of coexistence, as the pathogen is absent, geographic refuges are important because they allow host persistence in environments that would be suitable for the pathogen if it was present. For example, the green and golden bell frog (*Litoria aurea*) has experienced major declines across eastern Australia, but has persisted at high abundance on an off-shore island that is environmentally and climatically suitable for *Bd* (Stockwell et al., 2015a). Although geographic refuges can support crucial populations of declining species, their long-term viability is threatened by the possible introduction of *Bd*. Management of geographic refuges must focus on preventing *Bd* introduction, through the implementation of strict biosecurity protocols (see Phillott et al., 2010). Management of populations in geographic refuges may need to address additional issues, such as negative effects of geographic isolation and increased vulnerability to environmental or demographic stochasticity.

2.2. Contraction to climatic and environmental refuges

Far more common than geographic refuges is the contraction of amphibian species to climatic or environmental refuges (Figs. 1, 2). These are areas of a species' distributions that are climatically unsuitable for *Bd*, or where environmental conditions are either less favourable for *Bd* growth or more favourable for amphibian immunocompetence; leading to lower pathogenicity and/or virulence of *Bd*, with corresponding reductions in disease-induced mortality rates (Doddington et al., 2013; Puschendorf et al., 2011). In laboratory conditions, optimal growth of *Bd* occurs at temperatures ranging from 17 to 25 °C, and on either side of this range (5–16°C and 26–28 °C) growth is slow (Piotrowski et al., 2004). Prolonged exposure to temperatures above 30°C kills *Bd* and mortality is rapid at higher temperatures (e.g., 4 h at 37°C) (Johnson et al., 2003; Piotrowski et al., 2004). In addition to temperature limits on *Bd* occurrence, the fungus is not tolerant of desiccation, being killed by 1h of drying (Johnson et al., 2003). Therefore, areas where climatic conditions are outside the optimum for *Bd* persistence represent possible climate refuges, facilitating the persistence of susceptible species. The strong thermal and moisture constraints on *Bd* growth and survival likely underpin a global pattern of more severe amphibian declines in species restricted to upland (cool) areas, and wetter climates. For example, in Costa Rica and eastern Australia, there has been a marked pattern of severe amphibian declines in cool, moist upland regions, with many species contracting to hotter and drier lowland sites that are less conducive to *Bd* growth and survival (Fig. 2) (Puschendorf et al., 2009; Puschendorf et al., 2013).

In addition to climate refuges, local environmental conditions can be unfavourable for *Bd* growth and survival, or facilitate the host's immune response, allowing amphibian hosts to coexist with endemic *Bd*. These environmental refuges occur on smaller scales than climate refuges, and frequently exist within a broader climatic and environmental context that is favourable for *Bd.* For example, reduced rates of *Bd* infection and mortality have been found in lowland leopard frog (*Lithobates yavapaiensis*) populations in North America that occupy thermal springs where the water temperatures exceed 30^{o}C (Forrest and Schlaepfer, 2011; Savage et al., 2011). However, temperatures need not be close to the pathogen's upper tolerance for small-scale thermal refuges to occur. Heard et al. (2014) documented a strong negative relationship between water temperature (from 13-27 °C) and infection prevalence and intensity among growling grass frogs (*Litoria raniformis*) in Australia, and subsequently demonstrated that frog populations in relatively warm wetlands with low infection prevalence have substantially higher annual probabilities of population persistence (Heard et al., 2015). Heard et al. (2014) found the same for slightly saline wetlands, due to the negative effect of salinity on the prevalence of infections and disease-associated mortality (see also Stockwell et al., 2015b). The European midwife toads (*Alytes* spp.) provide further examples of environmental refuges. A population of the Mallorcan midwife toad (*A. muletensis*) occupying a narrow canyon is declining because stream water temperature is cool and more conducive to *Bd*, while a nearby population occupying a wider canyon is stable due to higher water temperatures, limiting fungus performance (Doddington et al., 2013). Similarly, in the Pyrenees, *Bd* has a wide elevational distribution in populations of the European midwife toad (*A. obstetricans)*, yet disease outbreaks and mortality are observed only in a small elevational range, corresponding with optimal conditions for *Bd* (Walker et al., 2010).

Environmental refuges also can occur as a result of spatially variable biotic processes that influence *Bd* occurrence and abundance. For example, *Bd* prevalence and infection intensity in French Pyrenean populations of *A. obstetricans* are influenced by the abundance of micro-predators that consume *Bd* zoospores (Schmeller et al., 2013). Similarly, the distribution of non-susceptible reservoir hosts also can produce environmental refuges. Amphibians vary in their susceptibility to *Bd*, meaning that those species that can persist in high abundance despite infections can amplify the prevalence of the fungus in sympatric, highly susceptible species (Brannelly et al., 2018). Environmental refuges may then exist for susceptible species under conditions that exclude the reservoir hosts. For example, the northern corroboree frog (*Pseudophryne pengilleyi*) has been extirpated from sites where the non-declining common eastern froglet (*Crinia signifera*) – a reservoir host – occurs in high abundance (Scheele et al., 2017b). Refuges for *P. pengilleyi* occur where habitat conditions are unfavourable for *C. signifera*, and the resulting low prevalence of *Bd* allows for *P. pengilleyi* persistence (Scheele et al., 2017b).

While the concept of refuges is not new to conservation, there are very few examples of this concept being integrated into the conservation of disease-threatened amphibians. However, significant management implications (and opportunities) arise from the occurrence (and recognition) of refuges from *Bd*. For example, where a substantial proportion of the original range of a declining species occurs in climatic refuges, active management of these populations may not be needed. Even in cases where species have lost a large portion of their former distribution, population stability in climatic refuges should be an important criteria for prioritizing conservation funding, as focusing management and monitoring efforts on such species may divert funds away from other species in more immediate need. Conversely, for species restricted to small-scale climatic or environmental refuges, it is crucial to locate these areas with thorough surveys of the historic range and to quantify the mechanism(s) underpinning population persistence (see section 3.1).

Examining underlying mechanisms is important in evaluating whether remnant populations are likely to be viable or whether active management is needed (see section 3.1). A thorough understanding of refuge characteristics also can inform searches for other refuges, and niche-based models may be used to aid the identification of sites where highly endangered species could be (re)established (Guisan et al., 2006). An illustrative example of the effectiveness of conservation focused on refuge characteristics is the case of the critically endangered armoured mist frog (*Litoria lorica*) in northern Australia. Initial survey efforts focused on examining mechanisms underpinning population persistence in the environmental refuge where the species was rediscovered (Puschendorf et al., 2011). Subsequent efforts then focused on surveying other potential refuges with similar characteristics, and when no further populations were found, a translocation was used to establish a second population at one of these refuge sites (Hoskin and Puschendorf, 2014).

For other species that remain more widely distributed, the stability of population networks may be reliant on particular environmental refuges that act as crucial source populations (Heard et al., 2015; see further below). Such refuges must be targets for protection from other threats, and should be the focus of active management that either enhances or maintains their refugial properties (Heard et al., 2018). Similarly, where created habitat can be engineered to have refugial properties from *Bd*, habitat creation schemes may reduce extinction risk significantly (Heard et al., 2018). Finally, populations in refuges are particularly important to monitor for several reasons. First, refuges may not represent static entities and may be vulnerable to changing climatic conditions or the introduction of new *Bd* lineages. Second, certain types of refuges may play a potentially important role in the long-term evolution of disease tolerance and resistance. When conditions are optimal for *Bd*, slight natural variation in resistance – upon which natural selection could act – is likely to be swamped by the very high virulence (and associated mortality) of *Bd*. However, in environmental refuges where *Bd* occurs but disease associated mortality rates are lower, slight fitness advantages could be selected for. Research and monitoring of populations in refuges is therefore important for understanding some of the mechanisms allowing long-term coexistence of amphibians and endemic *Bd*, developing and refining management interventions (see section 3.1), and ensuring populations are not experiencing slow, cryptic declines as described by Valenzuela-Sánchez et al. (2017).

2.3. Changes in amphibian habitat use

Small-scale habitat selection may facilitate coexistence of susceptible species with *Bd* under particular environmental conditions. In tropical northern Australia, Rowley and Alford (2013) showed in three frog species, that an individuals' probability of infection in the wild exhibited a strong negative correlation with time spent above 25^{o}C. Similarly, Richards-Zawacki (2010) reported that golden frogs (*Atelopus zeteki*) modified their thermoregulatory behaviour during a *Bd* outbreak in Panama, with a significant increase in mean body temperature across the population. Examining how temperature influences infection dynamics, Greenspan et al. (2017), demonstrated that frogs exposed daily to temperatures of 29^{o}C for four hours (mimicking temperature profiles obtained from wild frogs) experienced significant decreases in infection intensity and mortality compared to frogs kept at a constant 18^{o}C. From a management perspective, the fact that warmer body temperatures, even for short periods, can reduce infection risk opens the opportunity to trial management actions that manipulate habitat to facilitate thermoregulatory response, or provision of artificially warm micro-refuges where infected individuals could clear infection in the wild. In the case of habitat manipulations, modifications should be small-scale and implemented with appropriation caution to prevent unintended consequences. The potential of such methods is highlighted by research on endemically infected populations of common mist frogs (*Litoria rheocola*), which found that *Bd* infection prevalence declined after a tropical cyclone reduced stream shading by trees, increasing insolation and thermoregulatory opportunities for these frogs (Roznik et al., 2015b).

2.4. Altered population dynamics

Populations and population networks are stable if there is a balance between gains and losses (Schmidt et al., 2005). Even within climatic and environmental refuges, endemic *Bd* may drive population declines, because it continues to represent a significant source of both juvenile and adult mortality. For example, in eastern Australia, *Bd* infections remain a significant source of adult mortality for at least six hylid frog species that declined sharply during initial epidemics (*Litoria aurea, L. pearsoniana, L. raniformis, L. rheocola, L. spenceri and L. verreauxii alpina*), although at least some of these species have stabilized in climatic and environmental refuges over the last two decades (Grogan et al., 2016; Heard et al., 2014; Hunter et al., 2018; Murray et al., 2009; Pickett et al., 2014; Scheele et al., 2015). Likewise, *Bd* infections reduce annual survival rates of boreal toads (*Bufo boreas*) by between 31–42% in the Rocky Mountains of western U.S.A., leading to slow, ongoing population declines (Pilliod et al., 2010). In contrast to the Australian examples, however, where populations persist at lower elevations, high-elevation sites represent climatic refuges for *B. boreas*, due to temperature regimes that are below the thermal optimum for *Bd* growth (Mosher et al., 2018).

Amphibian populations such as these, which are subject to ongoing disease-induced mortality, can experience severe age structure truncation. Significant adult mortality leads to left-biased age structures, numerically dominated by juveniles, sub-adults and young adults. Scheele et al. (2016) provide a striking example in alpine tree frog (*Litoria verreauxii alpina*): populations with endemic *Bd* did not support individuals older than three years of age, while populations without *Bd* contained individuals up to seven years of age. Truncation of population age structure reduces population resilience and leads to increased sensitivity to both demographic and environmental stochasticity (Rouyer et al., 2012). For amphibian populations afflicted by *Bd*, in which survival rates are already depressed, spikes in mortality or recruitment failure associated with stochastic events can drive local extinction (Heard et al., 2015). Adult longevity among some species afflicted by *Bd* may fall to as low as one to two years post metamorphosis, allowing individual participation in only a single breeding season (Heard et al., 2012; Lampo et al., 2012; Pickett et al., 2014; Scheele et al., 2016), or no breeding at all in species that take longer to reach maturity (see section 3.1). Under this extreme scenario, formerly iteroparous species are pushed towards semelparity, and recruitment failure for even a single year may lead to local extinction (Scheele et al., 2016). Aquatic-breeding amphibians are particularly susceptible in this regard, with catastrophic tadpole mortality and recruitment failure being a common occurrence (Alford and Richards, 1999).

Three important consequences arise from these changes in demography and population dynamics in *Bd*-afflicted species. First, the persistence of *Bd*-challenged populations is likely to be increasingly dependent on consistent recruitment. Second, population networks may be destabilized. Third, life history traits may come under strong selection pressure in response to altered mortality schedules. We discuss each of these considerations in more detail below.

Due to increased adult mortality, *Bd*-challenged populations are likely to display greater reliance on consistent metamorph production and survival of post-metamorphic juveniles for regional persistence. Muths et al. (2011) provide an example of a compensatory response in a population of *B. boreas*, in which high and consistent recruitment facilitated coexistence with *Bd* despite *Bd*-induced mortality of adults. Scheele et al. (2015) similarly documented compensatory recruitment in *L. verreauxii alpina* populations and Spitzen-van der Sluijs et al. (2017) reported analogous results for yellow-bellied toads (*Bombina variegata)*. Examples such as these allow us to infer that population networks of species afflicted by *Bd* may rely heavily on ‘source’ populations where recruitment is high and consistent through time. In turn, we may infer that habitat patches with features that facilitate recruitment stability may become crucial for persistence. An example is the reliance of *L. verreauxii alpina* on permanent ponds in temperate Australia, despite the largest populations historically occurring in ephemeral wetlands (Scheele et al., 2016). This pattern may be replicated in at least two other frog species (*L. aurea* and *L. raniformis*) in eastern Australia that are afflicted by *Bd*, for which populations occupying permanent wetlands have much higher rates of persistence (e.g. Heard et al., 2013; Valdez et al., 2015).

Heightened adult mortality in *Bd*-afflicted populations is likely to destabilize the dynamics of population networks. Many amphibian species display relatively high rates of local extinction (due to their inherent sensitivity to environmental stochasticity, as above), and rely on similarly high rates of population recolonization for regional persistence (Hecnar and M'Closkey, 1996). However, high recolonization rates require high densities of populations and source populations which produce emigrants, given the generally sharp decay in dispersal rates with distance in amphibians (Smith and Green, 2005). Increased rates of local extinction induced by *Bd*, coupled with lower densities of populations and greater sensitivity to recruitment failure, can unravel these dynamics. For example, Heard et al. (2015) used simulations to demonstrate that metapopulations of their study species (*L. raniformis*) could rapidly collapse if environmental refuges from *Bd* and adequate connectivity among populations were not maintained.

Increased mortality in *Bd*-challenged populations has been associated with earlier host maturation, as has been demonstrated in *L. verreauxii alpina* in eastern Australia (Scheele et al., 2017d). Increased extrinsic mortality favours greater allocation of resources to early reproduction as a means of increasing the chance of reproducing before death (Stearns et al., 2000). Whether earlier maturation in *Bd*-challenged amphibian populations represents phenotypic plasticity (in response to altered resource dynamics) or an evolutionary response remains unclear, although both mechanisms could operate in concert (Scheele et al., 2017d). Further, a number of studies have reported increased energy allocation to reproduction in response to *Bd* infection. For example, *Bd*-infected male frogs appear to call more intensely than uninfected males (An and

Waldman, 2016; Roznik et al., 2015a). Such responses highlight the diverse range of processes acting in populations with endemic *Bd*.

Recognizing changes in population dynamics arising from endemic *Bd* has tangible outcomes for management (see section 3.1). As alluded to above, habitat-based management that focusses on reducing susceptibility to recruitment failure may be vital, particularly when the capacity to offset high rates of disease-induced mortality is minimal. Scheele et al (2016) provides a good example, showing that permanent wetlands are now crucial refuges for *L. verreauxii alpina* persistence and the consequent value of artificial wetlands for the conservation of this species.Similarly, Heard et al. (2018) simulated the capacity of wetland creation to mitigate the impacts of *Bd* on *L. raniformis* metapopulations in southern Australia, by increasing the number of environmental refuges from *Bd* in the network, and increasing both metapopulation size and connectivity (where the latter stems from greater densities of populations in the network and lower inter-patch distances, increasing the number of immigrants across the system). Their work demonstrates that such schemes could markedly reduce metapopulation extinction risk for *Bd*-challenged species. Lastly, for populations dependent on compensatory recruitment, we should recognize their increased vulnerability to habitat degradation (particularly the factors that determine production of metamorphs), short-term resource shortages and climatic variability (Spitzen-van der Sluijs et al., 2017).

Investigating how habitat conditions influence recruitment and population growth rates, and subsequently compensatory capacity, could present managers with novel management options. For example in California, Knapp et al. (2016) showed that reduced pressure from introduced predatory fish was partially responsible for the recovery of the yellow-legged frog (*Rana sierra)* despite the continued impacts associated with *Bd*, due to the resulting increase in tadpole and metamorph survival rates. With invasive predators being key drivers of reproductive failure for numerous amphibian species (particularly fish; Knapp and Matthews, 2000), management that delivers predator-free breeding sites (either by their construction or by elimination from already invaded sites) could prove a highly effective approach for conserving disease-challenged populations.

3. Key steps for managing amphibian species threatened by endemic chytridiomycosis

Batrachochytrium dendrobatidis poses a major challenge to the management of amphibian populations. Despite recognition of the problem, there has been very little progress on mitigating the impact of chytridiomycosis and stabilizing declining species in the wild (Garner et al., 2016; Scheele et al., 2014b). More broadly, effective management of wildlife pathogens has proven elusive in a diverse range of contexts (Langwig et al., 2015). In this review, we examined ecological factors that contribute to the coexistence of susceptible amphibian species with endemic *Bd*. This provides a foundation to develop mitigation strategies based on the environmental part of the host-pathogen-environment triangle. This is in contrast to previous efforts that have focused directly on either the hosts and/or the pathogen. We propose the development and trialling of new management approaches that focus on achieving coexistence through either: (1) manipulating environmental conditions to decrease the pathogenicity and/or virulence of *Bd*, or (2) bolstering population resilience to disease-induced mortality, by facilitating compensatory mechanisms such as increased recruitment success and consistency, and/or reduced mortality from other sources. These approaches are likely to be widely applicable as environmental conditions can strongly mediate the impact of biotic threats (Scheele et al., 2017a, 2018a), and because most amphibian species are endangered by multiple threats (Grant et al., 2016). Below we outline four key steps that involve a mixture of research and management that can help achieve coexistence of susceptible amphibian species with *Bd*.

3.1. Key steps towards achieving coexistence of declining amphibian species with Bd

1. <u>Define clear management objectives.</u> Identifying clear, quantifiable management objectives is a fundamental initial step. Objectives must be clearly linked to conservation status, but tightly defined in terms of demographic responses and timelines (for example, reduce rate of decline by 10% over five years, increase occupancy by 20% over 10 years). Objectives must be realistic under legal and financial constraints and should be developed with input from scientists, managers, and stakeholders (Converse and Grant, 2019 - This issue; Gerber et al., 2018).

2. Gather detailed information on species' contemporary distribution and status, recognizing that baselines have shifted. As outlined in the preceding sections, the emergence of *Bd* has fundamentally reshaped the ecology of many species, demonstrating that the realized niche of species is not a fixed entity: it changes as the biotic context changes. As such, management must be informed by up-to-date information on species ranges (Scheele et al., 2014a). Additionally, the utility of information on species ecology, such as longevity or annual survival rates, collected before the emergence of *Bd* should be re-evaluated as it may not reflect the current reality with endemic *Bd*. The phenomenon of shifting baselines – where the former abundance or distribution of a species prior to its decline is not recognized, and the current greatly reduced state is perceived as 'normal' (Pauly, 1995) – is highly relevant to many amphibian species that have declined due to *Bd.* There are two management considerations arising from shifting baselines. First, for declines that occurred decades ago, there may be a failure to appreciate the diversity of habitat across which the species formally occurred, unnecessarily restricting the scope of management. Second, in the context of recent declines, failure to shift baselines could result in poorly targeted management that ignores the new reality of endemic *Bd*.

3. Investigate mechanism(s) underpinning coexistence of populations with *Bd*. For susceptible species that persist in some locations, it is important to investigate *Bd*-host dynamics to evaluate risk of extinction, the mechanisms facilitating coexistence, and if required, guide the development of appropriate management actions. This information can be used to model a range of scenarios to best target management interventions, at both the population and network scale. Possible management strategies include either increasing geographic availability of environmental conditions that allow a species to persist with *Bd* (habitat creation or assisted colonization), and/or managing interacting factors to allow species to persist despite some level of mortality from *Bd*. This may entail a mix of both creative and pragmatic management initiatives. The former may involve small-scale interventions targeting particular mechanisms of disease mitigation (e.g., removal of reservoir hosts or creation of thermal refuges) and the latter may include management regimes that have historically been considered undesirable (e.g., canopy thinning, or livestock grazing of wetland edges to clear vegetation to increase insolation and reduce environmental suitability for *Bd*). We stress that habitat modifications should be highly targeted and small-scale, and should be conducted only after a thorough evaluation of potential unintended negative effects on both the target species, and other species in the

ecosystem. This requires assessing trade-offs. For example, canopy thinning may reduce environmental suitability for *Bd*, but could also remove key microhabitats for some species, altering trophic networks upon which they rely, or desiccate vital shelter sites.

<u>4. Implement management in an adaptive management framework</u>. In all cases, the decision of what management to implement where will be taken under variable levels of uncertainty (Converse and Grant, 2019 - This issue; Smalling et al., 2019 - This issue; Sterrett et al., 2019 - This issue). A range of decision support tools, such as structured decision making, can be used to improve decision making and identify sources of uncertainty (see case study by Converse et al., 2017). Importantly, management actions should be treated as experiments and implemented in an adaptive framework, with iterative adjustments to improve efficiency (Canessa et al., 2019 - This issue).

More broadly, management success is dependent on developing and maintaining teams that involve a range of contributors. For example, conservation programs that have prevented the extinction of several critically endangered frog species in Australia threatened by *Bd* (*Pseudophryne pengilleyi*, *P. corroboree* and *L. spenceri*) involve strong partnerships between government managers responsible for implementation of on-ground actions, government and non-government conservation organisations, and scientists from multiple disciplines. Importantly, partners are involved throughout the research-management cycle; from identifying management objectives and research questions to implementation and evaluation of management effectiveness (Scheele et al., 2018b).

4. Conclusion

The global emergence of *Bd* and subsequent amphibian declines represent an unprecedented conservation challenge. Never before has disease been identified as a key threat to such a large number and diverse range of species. While many species extinctions have already occurred during epidemics, the focus in many regions of the globe is now on preventing further losses as the pathogen transitions to endemicity. Our review highlights a diverse range of processes that can lead to coexistence with *Bd*. We argue, on the basis of these insights, that conservation actions for susceptible amphibians with endemic *Bd* should focus on manipulating environmental conditions to decrease suitability for *Bd*, and/or facilitating demographic mechanisms that allow populations to compensate for *Bd*-associated mortality, and to persist despite it. Conserving species at risk of extinction requires a proactive mindset that accepts the new ecological reality of endemic *Bd* and uses an adaptive management framework to implement novel management approaches.

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5. References

Alford, R.A., Richards, S.J., 1999. Global amphibian declines: A problem in applied ecology. Annu. Rev. Ecol. Syst. 30, 133-165.

An, D., Waldman, B., 2016. Enhanced call effort in Japanese tree frogs infected by amphibian chytrid fungus. Biol. Lett. 12, 20160018.

Berger, L., et al., 1998. Chytridiomycosis causes amphibian mortality associated with population declines in the rain forests of Australia and Central America. Proc. Natl. Acad. Sci. USA 95, 9031-9036.

Brannelly, L., Webb, R., Hunter, D., Clemann, N., Howard, K., Skerratt, L., Berger, L., Scheele, B., 2018. Non-declining amphibians can be important reservoir hosts for amphibian chytrid fungus. Anim. Conserv. 21, 91-101.

Canessa, S., Ottonello, D., Rosa, G., Salvidio, S., Oneto, F., 2019 - This issue. Adaptive management for amphibian recovery programs: a real-world application. Biol. Conserv.

Converse, S.J., Bailey, L.L., Mosher, B.A., Funk, W.C., Gerber, B.D., Muths, E., 2017. A model to inform management actions as a response to chytridiomycosis-associated decline. EcoHealth 14, 144-155.

Converse, S.J., Grant, E.H.C., 2019 - This issue. A rational, structured approach to deciding and acting in the face of amphibian declines. Biol. Conserv.

Doddington, B.J., Bosch, J., Oliver, J.A., Grassly, N.C., Garcia, G., Schmidt, B.R., Garner, T.W.J., Fisher, M.C., 2013. Context-dependent amphibian host population response to an invading pathogen. Ecology 94, 1795-1804.

Forrest, M.J., Schlaepfer, M.A., 2011. Nothing a hot bath won't cure: Infection rates of amphibian chytrid fungus correlate negatively with water temperature under natural field settings. PLoS ONE 6, doi: 10.1371/journal.pone.0028444.

Garner, T.W., Schmidt, B.R., Martel, A., Pasmans, F., Muths, E., Cunningham, A.A., Weldon, C., Fisher, M.C., Bosch, J., 2016. Mitigating amphibian chytridiomycoses in nature. Phil. Trans. R. Soc. B 371, 20160207.

Gerber, B.D., Converse, S.J., Muths, E., Crockett, H.J., Mosher, B.A., Bailey, L.L., 2018. Identifying species conservation strategies to reduce disease-associated declines. Conserv. Lett. 11, e12393.

Gillespie, G., Hunter, D., Berger, L., Marantelli, G., 2015. Rapid decline and extinction of a montane frog population in southern Australia follows detection of the amphibian pathogen *Batrachochytrium dendrobatidis*. Anim. Conserv. 18, 295-302.

Grant, E.H.C., et al., 2016. Quantitative evidence for the effects of multiple drivers on continental-scale amphibian declines. Sci. Rep. 6, 25625.

Greenspan, S.E., et al., 2017. Realistic heat pulses protect frogs from disease under simulated rainforest frog thermal regimes. Funct. Ecol. 31, 2274-2286.

Grogan, L.F., Phillott, A.D., Scheele, B.C., Berger, L., Cashins, S.D., Bell, S.C., Puschendorf, R., Skerratt, L.F., 2016. Endemicity of chytridiomycosis features pathogen over-dispersion. J. Anim. Ecol. 85, 806–816.

Guisan, A., Broennimann, O., Engler, R., Vust, M., Yoccoz, N.G., Lehmann, A., Zimmermann, N.E., 2006. Using niche-based models to improve the sampling of rare species. Conserv. Biol. 20, 501-511.

Heard, G.W., McCarthy, M.A., Scroggie, M.P., Baumgartner, J.B., Parris, K.M., 2013. A Bayesian model of metapopulation viability, with application to an endangered amphibian. Divers. Distrib. 19, 555-566.

Heard, G.W., Scroggie, M.P., Clemann, N., Ramsey, D.S.L., 2014. Wetland characteristics influence disease risk for a threatened amphibian. Ecol. Appl. 24, 650–662.

Heard, G.W., Scroggie, M.P., Malone, B.S., 2012. Classical metapopulation theory as a useful paradigm for the conservation of an endangered amphibian. Biol. Conserv. 148, 156-166.

Heard, G.W., Scroggie, M.P., Ramsey, D.S., Clemann, N., Hodgson, J.A., Thomas, C.D., 2018. Can habitat management mitigate disease impacts on threatened amphibians? Conserv. Lett. 11, e12375.

Heard, G.W., Thomas, C.D., Hodgson, J.A., Scroggie, M.P., Ramsey, D.S., Clemann, N., 2015. Refugia and connectivity sustain amphibian metapopulations afflicted by disease. Ecol. Lett. 18, 853-863.

Hecnar, S.J., M'Closkey, R.T., 1996. Regional dynamics and the status of amphibians. Ecology 77, 2091-2097.

Hoskin, C.J., Puschendorf, R., 2014. The importance of peripheral areas for biodiversity conservation: with particular focus on endangered rainforest frogs of the Wet Tropics and Eungella. Report to the National Environmental Research Program. (Reef and Rainforest Research Centre Limited: Cairns, Australia)

Hunter, D., Clemann, N., Coote, D., Gillespie, G., Hollis, G., Scheele, B., Philips, A., West, M., 2018. Frog declines and associated management response in south-eastern mainland Australia and Tasmania, In Status of Conservation and Decline of Amphibians: Australia, New Zealand, and Pacific Islands. eds H. Heatwole, J. Rowley, pp. 39-58. CSIRO Publishing.

Johnson, M.L., Berger, L., Philips, L., Speare, R., 2003. Fungicidal effects of chemical disinfectants, UV light, desiccation and heat on the amphibian chytrid *Batrachochytrium dendrobatidis*. Dis. Aquat. Org. 57, 255-260.

Johnson, M.L., Speare, R., 2005. Possible modes of dissemination of the amphibian chytrid *Batrachochytrium dendrobatidis* in the environment. Dis. Aquat. Org. 65, 181-186.

Knapp, R.A., Fellers, G.M., Kleeman, P.M., Miller, D.A., Vredenburg, V.T., Rosenblum, E.B., Briggs, C.J., 2016. Large-scale recovery of an endangered amphibian despite ongoing exposure to multiple stressors. Proc. Natl. Acad. Sci. USA 113, 11889-11894.

Knapp, R.A., Matthews, K.R., 2000. Non-native fish introductions and the decline of the mountain yellow-legged frog from within protected areas. Conserv. Biol. 14, 428-438.

Lampo, M., Celsa, S.J., Rodriguez-Contreras, A., Rojas-Runjaic, F., Garcia, C.Z., 2012. High turnover rates in remnant populations of the Harlequin frog *Atelopus cruciger* (Bufonidae): low risk of extinction? Biotropica 44, 420-426.

Langwig, K.E., et al., 2015. Context-dependent conservation responses to emerging wildlife diseases. Front. Ecol. Environ. 13, 195-202.

Leopardi, S., Blake, D., Puechmaille, S.J., 2015. White-nose syndrome fungus introduced from Europe to North America. Curr. Biol. 25, R217-R219.

Lewis, C., Richards-Zawacki, C.L., Ibáñez, R., Luedtke, J., Voyles, J., Houser, P., Gratwicke, B., 2019 - This issue. Conserving Panamanian harlequin frogs by integrating captive-breeding and research programs. Biol. Conserv.

Lips, K.R., 2016. Overview of chytrid emergence and impacts on amphibians. Phil. Trans. R. Soc. B 371, 20150465.

Lloyd-Smith, J.O., Cross, P.C., Briggs, C.J., Daugherty, M., Getz, W.M., Latto, J., Sanchez, M.S., Smith, A.B., Swei, A., 2005. Should we expect population thresholds for wildlife disease? Trends Ecol. Evol. 20, 511-519.

Longcore, J.E., Pessier, A.P., Nichols, D.K., 1999. *Batrachochytrium dendrobatidis* gen. et sp. nov., a chytrid pathogenic to amphibians Mycologia 91, 219-227.

Martel, A., et al., 2014. Recent introduction of a chytrid fungus endangers Western Palearctic salamanders. Science 346, 630-631.

Mendelson, J.I., Whitfield, S.M., Sredld, M.J., 2019 -This issue. A recovery engine strategy for amphibian conservation in the context of disease. Biol. Conserv.

Mosher, B.A., Bailey, L.L., Muths, E., Huyvaert, K.P., 2018. Host-pathogen metapopulation dynamics suggest high elevation refugia for boreal toads. Ecol. Appl. 28, 926-937.

Murray, K.A., Skerratt, L.F., Speare, R., McCallum, H., 2009. Impact and dynamics of disease in species threatened by the amphibian chytrid fungus, *Batrachochytrium dendrobatidis*. Conserv. Biol. 23, 1242-1252.

Muths, E., Scherer, R.D., Pilliod, D.S., 2011. Compensatory effects of recruitment and survival when amphibian populations are perturbed by disease. J. Appl. Ecol. 48, 873-879.

O'Hanlon, S.J., et al., 2018. Recent Asian origin of chytrid fungi causing global amphibian declines. Science 360, 621-627.

Pauly, D., 1995. Anecdotes and the shifting baseline syndrome of fisheries. Trends Ecol. Evol. 10, 430.

Phillott, A.D., Speare, R., Hines, H.B., Skerratt, L.F., Meyer, E., McDonald, K.R., Cashins, S.D., Mendez, D., Berger, L., 2010. Minimising exposure of amphibians to pathogens during field studies. Dis. Aquat. Org. 92, 175-185.

Pickett, E.J., Stockwell, M.P., Bower, D.S., Pollard, C.J., Garnham, J.I., Clulow, J., Mahony, M.J., 2014. Six-year demographic study reveals threat of stochastic extinction for remnant populations of a threatened amphibian. Austral Ecol. 39, 244-253.

Pilliod, D.S., Muths, E., Scherer, R.D., Bartelt, P.E., Corn, P.S., Hossack, B.R., Lambert, B.A., McCaffery, R., Gaughan, C., 2010. Effects of amphibian chytrid fungus on individual survival probability in wild boreal toads. Conserv. Biol. 24, 1259-1267.

Piotrowski, J.S., Annis, S.L., Longcore, J.E., 2004. Physiology of *Batrachochytrium dendrobatidis*, a chytrid pathogen of amphibians. Mycologia 96, 9-15.

Puschendorf, R., Carnaval, A.C., VanDerWal, J., Zumbado-Ulate, H., Chaves, G., Bolanos, F., Alford, R.A., 2009. Distribution models for the amphibian chytrid *Batrachochytrium dendrobatidis* in Costa Rica: proposing climatic refuges as a conservation tool. Divers. Distrib. 15, 401-408.

Puschendorf, R., Hodgson, L., Alford, R.A., Skerratt, L.F., VanDerWal, J., 2013. Underestimated ranges and overlooked refuges from amphibian chytridiomycosis. Divers. Distrib. 19, 1313-1321.

Puschendorf, R., Hoskin, C.J., Cashins, S.D., McDonald, K., Skerratt, L.F., VanDerWal, J., Alford, R.A., 2011. Environmental refuge from disease-driven amphibian extinction. Conserv. Biol. 25, 956-964.

Richards-Zawacki, C.L., 2010. Thermoregulatory behaviour affects prevalence of chytrid fungal infection in a wild population of Panamanian golden frogs. Proc. R. Soc. B 277, 519-528.

Rouyer, T., Sadykov, A., Ohlberger, J., Stenseth, N.C., 2012. Does increasing mortality change the response of fish populations to environmental fluctuations? Ecol. Lett. 15, 658-665.

Rowley, J.J.L., Alford, R.A., 2013. Hot bodies protect amphibians against chytrid infection in nature. Sci. Rep. 3, e1515.

Roznik, E.A., Sapsford, S.J., Pike, D.A., Schwarzkopf, L., Alford, R.A., 2015a. Condition-dependent reproductive effort in frogs infected by a widespread pathogen. Proc. R. Soc. B 282, 20150694.

Roznik, E.A., Sapsford, S.J., Pike, D.A., Schwarzkopf, L., Alford, R.A., 2015b. Natural disturbance reduces disease risk in endangered rainforest frog populations. Sci. Rep. 5.

Samuel, M.D., Woodworth, B.L., Atkinson, C.T., Hart, P.J., LaPointe, D.A., 2015. Avian malaria in Hawaiian forest birds: infection and population impacts across species and elevations. Ecosphere 6, art104.

Savage, A.E., Sredl, M.J., Zamudio, K.R., 2011. Disease dynamics vary spatially and temporally in a North American amphibian. Biol. Conserv. 144, 1910-1915.

Scheele, B.C., Foster, C.N., Banks, S.C., Lindenmayer, D.B., 2017a. Niche contractions in declining species: mechanisms and consequences. Trends Ecol. Evol. 32, 346-355.

Scheele, B.C., Foster, C.N., Banks, S.C., Lindenmayer, D.B., 2018a. The role of biotic interactions in the Niche Reduction Hypothesis: A reply to Doherty and Driscoll. Trends Ecol. Evol. 33, 148-149.

Scheele, B.C., Guarino, F., Osborne, W., Hunter, D.A., Skerratt, L.F., Driscoll, D.A., 2014a. Decline and re-expansion of an amphibian with high prevalence of chytrid fungus. Biol. Conserv. 170, 86-91.

Scheele, B.C., Hunter, D.A., Banks, S.C., Pierson, J.C., Skerratt, L.F., Webb, R., Driscoll, D.A., 2016. High adult mortality in disease-challenged frog populations increases vulnerability to drought. J. Anim. Ecol. 85, 1453-1460.

Scheele, B.C., Hunter, D.A., Brannelly, L.A., Skerratt, L.F., Driscoll, D.A., 2017b. Reservoir-host amplification of disease impact in an endangered amphibian. Conserv. Biol. 31, 592-600.

Scheele, B.C., Hunter, D.A., Grogan, L., Berger, L., Kolby, J., McFadden, M., Marantelli, G., Skerratt, L.F., Driscoll, D.A., 2014b. Interventions for reducing extinction risk in chytridiomycosis-threatened amphibians. Conserv. Biol. 28, 1195–1205.

Scheele, B.C., Hunter, D.A., Skerratt, L.F., Brannelly, L.A., Driscoll, D.A., 2015. Low impact of chytridiomycosis on frog recruitment enables persistence in refuges despite high adult mortality. Biol. Conserv. 182, 36-43.

Scheele, B.C., Legge, S., Armstrong, D.P., Copley, P., Robinson, N.M., Southwell, D.M., Westgate, M.J., Lindenmayer, D.B., 2018b. How to improve threatened species management: an Australian perspective. J. Environ. Manage. 223, 668-675.

Scheele, B.C., et al., 2017c. After the epidemic: Ongoing declines, stabilizations and recoveries in amphibians afflicted by chytridiomycosis. Biol. Conserv. 206, 37-46.

Scheele, B.C., Skerratt, L.F., Hunter, D.A., Banks, S.C., Pierson, J.C., Driscoll, D.A., Byrne, P.G., Berger, L., 2017d. Disease-associated change in an amphibian life-history trait. Oecologia 184, 825-833.

Schmeller, D.S., et al., 2013. Microscopic aquatic predators strongly affect infection dynamics of a globally emerged pathogen. Curr. Biol. 24, 176-180.

Schmidt, B.R., Feldmann, R., Schaub, M., 2005. Demographic processes underlying population growth and decline in *Salamandra salamandra*. Conserv. Biol. 19, 1149-1156.

Scholthof, K.-B.G., 2007. The disease triangle: pathogens, the environment and society. Nat. Rev. Microbiol. 5, 152.

Smalling, K.L., Eagles-Smith, C.A., Katz, R.A., Grant, E.H.C., 2019 - This issue. Managing the trifecta of disease, climate, and contaminants: Searching for robust choices under multiple sources of uncertainty. Biol. Conserv.

Smith, M.A., Green, D.M., 2005. Dispersal and the metapopulation paradigm in amphibian ecology and conservation: are all amphibian populations metapopulations? Ecography 28, 110-128.

Spitzen-van der Sluijs, A., Canessa, S., Martel, A., Pasmans, F., 2017. Fragile coexistence of a global chytrid pathogen with amphibian populations is mediated by environment and demography. Proc. R. Soc. B 284, 20171444.

Stearns, S., Ackermann, M., Doebeli, M., Kaiser, M., 2000. Experimental evolution of aging, growth, and reproduction in fruitflies. Proc. Natl. Acad. Sci. USA 97, 3309-3313.

Sterrett, S.C., Katz, R.A., Brand, A.B., Fields, W.R., Dietrich, A.E., Hocking, D.J., Foreman, T.M., Wiewel, A.N.M., Grant, E.H.C., 2019 -This issue. Proactive management of amphibians: challenges and opportunities. Biol. Conserv.

Stockwell, M.P., Bower, D.S., Bainbridge, L., Clulow, J., Mahony, M.J., 2015a. Island provides a pathogen refuge within climatically suitable area. Biodivers. Conserv. 24, 2583-2592.

Stockwell, M.P., Storrie, L.J., Pollard, C.J., Clulow, J., Mahony, M.J., 2015b. Effects of pond salinization on survival rate of amphibian hosts infected with the chytrid fungus. Conserv. Biol. 29, 391-399.

Tompkins, D., Begon, M., 1999. Parasites can regulate wildlife populations. Parasitol. Today 15, 311-313.

Tompkins, D.M., Sainsbury, A.W., Nettleton, P., Buxton, D., Gurnell, J., 2002. Parapoxvirus causes a deleterious disease in red squirrels associated with UK population declines. Proc. R. Soc. B 269, 529-533.

Valdez, J.W., Stockwell, M.P., Klop-Toker, K., Clulow, S., Clulow, J., Mahony, M.J., 2015. Factors driving the distribution of an endangered amphibian toward an industrial landscape in Australia. Biol. Conserv. 191, 520-528.

Valenzuela-Sánchez, A., Schmidt, B.R., Uribe-Rivera, D.E., Costas, F., Cunningham, A.A., Soto-Azat, C., 2017. Cryptic disease-induced mortality may cause host extinction in an apparently stable host–parasite system. Proc. R. Soc. B 284, 20171176.

Voyles, J., et al., 2018. Shifts in disease dynamics in a tropical amphibian assemblage are not due to pathogen attenuation. Science 359, 1517-1519.

Walker, S.F., et al., 2010. Factors driving pathogenicity vs. prevalence of amphibian panzootic chytridiomycosis in Iberia. Ecol. Lett. 13, 372-382.

Figure captions

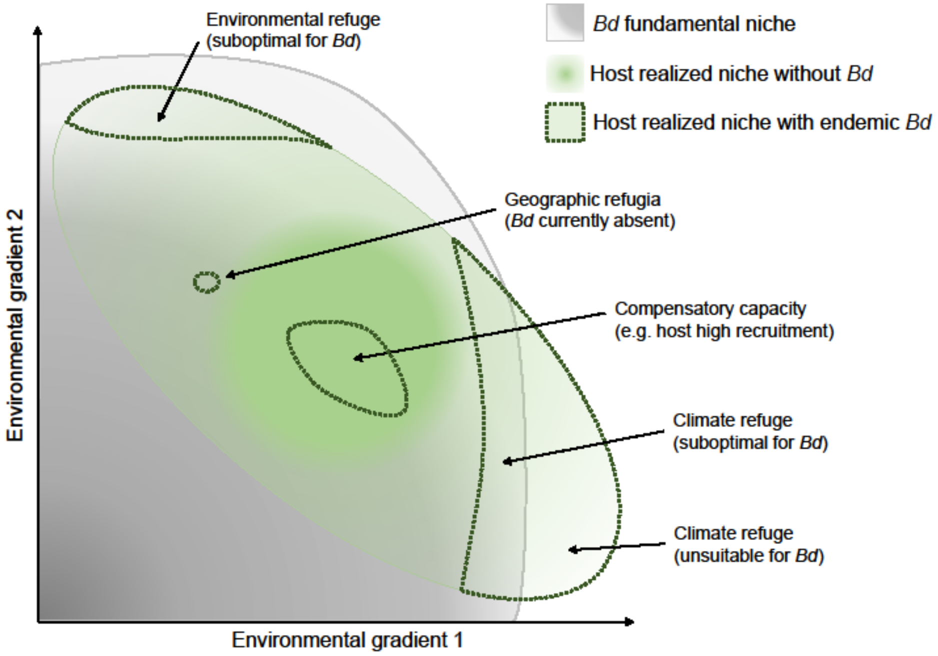

Figure 1. Possible host responses to *B. dendrobatidis*, represented in two-dimensional environmental space, with reference to the environmental niche of both the host and the pathogen. Performance of both species declines with the decreasing density of shading within their niche. Host responses illustrated include contraction to geographic refuges and contraction to climatic and environmental refuges, including both environments unfavourable for the pathogen, as well as environments where amphibians have high compensatory capacity (e.g. an environment where the species can maintain a consistent, high recruitment rate to offset high adult mortality). An individual host species may show none or all of these responses across different parts of its range.

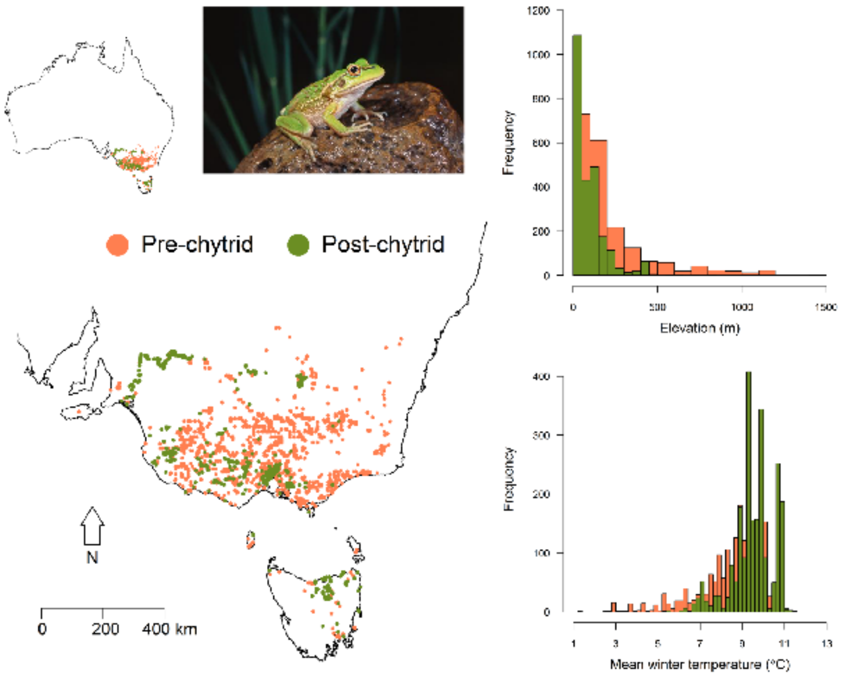

Figure 2. The growling grass frog (*Litoria raniformis*) experienced major declines in south-eastern Australia, which were partly driven by *Batrachochytrium dendrobatidis* epidemics. Declines were most severe at higher elevations where environmental conditions are optimal for *Bd* and where the species has reduced capacity to tolerate elevated adult mortality. The species has now contracted to climatic and environmental refuges, although *Bd*-associated adult mortality remains high (Heard et al., 2014). This figure shows the spatial, elevational and climatic distribution of the species before and after the primary declines driven by *Bd*, where pre-decline records are those prior to or very shortly after the arrival of *Bd* in Australia (1980 or before), and post-decline records are those from 2000 or later, by which time *Bd* is thought to have spread across the entire range of the species. Climate is represented here by annual mean winter temperatures. Data sourced from the Atlas of Living Australia (ala.org.au) and WorldClim (worldclim.org).

Supplementary Material

Living with the enemy: facilitating amphibian coexistence with disease

Supplementary text on the role of host-immune responses and shifts in pathogen virulence in achieving coexistence of susceptible amphibian species with *Batrachochytrium dendrobatidis* (hereafter *Bd*).

Immune responses

Evolution of increased amphibian host tolerance and resistance (immunity) can facilitate coexistence of amphibian species with *Bd* after a transition to endemicity. Emerging pathogens exert strong selection pressure in naïve host populations, and there are many examples of natural selection for increased host resistance resulting in pathogen-host coexistence (see review by Altizer et al., 2003). Reduced host susceptibility to *Bd* has been hypothesized as the mechanism underpinning the persistence or recovery of chytridiomycosis-affected amphibian species from the Americas (Knapp et al., 2016; Savage and Zamudio, 2011; Voyles et al., 2018) and Australia (Newell et al., 2013; Scheele et al., 2014). In the case of the recovery of the Sierra Nevada yellow-legged frog (*Rana sierrae*), Knapp et al. (2016) found that individuals from long-infected populations that were persisting with endemic *Bd* infection, were significantly less susceptible to infection than individuals from naïve populations. Similarly, documenting the recovery of several Panamanian species a decade after the initial outbreak of *Bd,* Voyles et al. (2018) found differences in skin secretions that inhibit *Bd* growth in frogs with different exposure histories, potentially representing a mechanism facilitating increased host resistance. Further, there is evidence for directional selection of major histocompatibility complex (MHC) alleles related to resistance in amphibian species, providing an additional putative evolutionary mechanism (Bataille et al., 2015; Savage and Zamudio, 2016).

From a management perspective, efforts to increase host resistance could be achieved through: 1) augmentation (e.g. bolstering population abundance or managing other threats) of wild populations under natural selection for increased resistance until they become self-sustaining (although this approach could compromise the selection process), and 2) identification of genetic markers for resistance combined with targeted selective breeding programs and/or gene editing technologies (Garner et al., 2016). Currently, there are no successful examples of either of the abovementioned approaches, but both remain active areas of research. In the case of selective breeding, success is likely to be dependent on pre-existing variation in susceptibility between individuals within a species, while this obstacle could be overcome with gene editing approaches.

Shifts in pathogen virulence

Reduction in the virulence of *Bd* following a transition to endemicity could facilitate the coexistence with susceptible amphibian species. Reduced pathogen virulence has been reported in a number of other host-pathogen systems, such as myxomatosis in European rabbits (*Oryctolagus cuniculus*) (Altizer et al., 2003). However, while there is evidence for variation in virulence between different *Bd* lineages (O'Hanlon et al., 2018), there is currently no evidence for pathogen attenuation following a transition to endemicity (Voyles et al., 2018). For example, a comparison of historical and contemporary *Bd* isolates in Panama found no evidence for pathogen attenuation over the 11-13 years since initial epidemics (Voyles et al., 2018). These findings are in sharp contrast to rapid reductions in virulence reported in the laboratory with frequent passage of *Bd* (Refsnider et al., 2015). Maintenance of high virulence in the wild may be related to the broad host range of *Bd* (Olson et al., 2013) and large variation in susceptibility between sympatric amphibian species (Fisher et al., 2009), maintaining high selection pressure for virulence. From a management perspective, methods to manipulate *Bd* virulence have yet to be investigated.

References

Altizer, S., Harvell, D., Friedle, E., 2003. Rapid evolutionary dynamics and disease threats to biodiversity. Trends Ecol. Evol. 18, 589-596.

Bataille, A., Cashins, S.D., Grogan, L., Skerratt, L.F., Hunter, D., McFadden, M., Scheele, B., Brannelly, L.A., Macris, A., Bell, S., Berger, L., Harlow, P.S., 2015. Susceptibility of amphibians to chytridiomycosis is associated with MHC class II conformation. Proc. R. Soc. Lond., Ser. B: Biol. Sci. 282, 20143127.

Fisher, M.C., Garner, T.W.J., Walker, S.F., 2009. Global emergence of *Batrachochytrium dendrobatidis* and amphibian chytridiomycosis in space, time, and host. Annu. Rev. Microbiol. 63, 291-310.

Garner, T.W., Schmidt, B.R., Martel, A., Pasmans, F., Muths, E., Cunningham, A.A., Weldon, C., Fisher, M.C., Bosch, J., 2016. Mitigating amphibian chytridiomycoses in nature. Phil. Trans. R. Soc. B 371, 20160207.

Knapp, R.A., Fellers, G.M., Kleeman, P.M., Miller, D.A., Vredenburg, V.T., Rosenblum, E.B., Briggs, C.J., 2016. Large-scale recovery of an endangered amphibian despite ongoing exposure to multiple stressors. Proc. Natl. Acad. Sci. USA 113, 11889-11894.

Newell, D.A., Goldingay, R.L., Brooks, L.O., 2013. Population recovery following decline in an endangered stream-breeding frog (*Mixophyes fleayi*) from subtropical Australia. PloS ONE 8, doi: 10.1371/journal.pone.0058559.

O'Hanlon, S.J., Rieux, A., Farrer, R.A., Rosa, G.M., Waldman, B., Bataille, A., Kosch, T.A., Murray, K.A., Brankovics, B., Fumagalli, M., Martin, M.D., Wales, N., Alvarado-Rybak, M., Bates, K.A., Berger, L., Böll, S., Brookes, L., Clare, F., Courtois, E.A., Cunningham, A.A., Doherty-Bone, T.M., Ghosh, P., Gower, D.J., Hintz, W.E., Höglund, J., Jenkinson, T.S.J., Lin, C.-F., Laurila, A., Loyau, A., Martel, A., Meurling, S., Miaud, C., Minting, P., Pasmans, F., Schmeller, D.S., Schmidt, B.R., Shelton, J.M.G., Skerratt, L.F., Smith, F., Soto-Azat, C., Spagnoletti, M., Tessa, G., Toledo, L.F., Valenzuela-Sánchez, A., Verster, R., Vörös, J., Webb, R.J., Wierzbicki, C., Wombwell, E., Zamudio, K.R., Aanensen, D.M., James, T.Y., Gilbert, M.T.P., Weldon, C., Bosch, J., Balloux, F., Garner, T.W.J., Fisher, M.C., 2018. Recent Asian origin of chytrid fungi causing global amphibian declines. Science 360, 621-627.

Olson, D.H., Aanensen, D.M., Ronnenberg, K.L., Powell, C.I., Walker, S.F., Bielby, J., Garner, T.W., Weaver, G., Fisher, M.C., 2013. Mapping the global emergence of *Batrachochytrium dendrobatidis*, the amphibian chytrid fungus. PLoS ONE 8, doi.org/10.1371/journal.pone.0056802.

Refsnider, J.M., Poorten, T.J., Langhammer, P.F., Burrowes, P.A., Rosenblum, E.B., 2015. Genomic correlates of virulence attenuation in the deadly amphibian chytrid fungus, *Batrachochytrium dendrobatidis*. G3: Genes, Genomes, Genetics, g3. 115.021808.

Savage, A.E., Zamudio, K.R., 2011. MHC genotypes associate with resistance to a frog-killing fungus. Proc. Natl. Acad. Sci. USA 108, 16705-16710.

Savage, A.E., Zamudio, K.R., 2016. Adaptive tolerance to a pathogenic fungus drives major histocompatibility complex evolution in natural amphibian populations. Proc. R. Soc. B 283, 20153115.

Scheele, B.C., Guarino, F., Osborne, W., Hunter, D.A., Skerratt, L.F., Driscoll, D.A., 2014. Decline and re-expansion of an amphibian with high prevalence of chytrid fungus. Biol. Conserv. 170, 86-91.

Voyles, J., Woodhams, D.C., Saenz, V., Byrne, A.Q., Perez, R., Rios-Sotelo, G., Ryan, M.J., Bletz, M.C., Sobell, F.A., McLetchie, S., 2018. Shifts in disease dynamics in a tropical amphibian assemblage are not due to pathogen attenuation. Science 359, 1517-1519.

Appendix A: A comprehensive list of articles consulted that examine amphibian host responses to epidemic and endemic *Batrachochytrium dendrobatidis*. This list has been provided so that researchers and managers considering implementing management approaches outlined in the main text can consult this list to identify the most relevant literature. The list is ordered by continent to assist easy interrogation.

Australia

Bataille, A., Cashins, S.D., Grogan, L., Skerratt, L.F., Hunter, D., McFadden, M., Scheele, B., Brannelly, L.A., Macris, A., Bell, S., Berger, L., Harlow, P.S., 2015. Susceptibility of amphibians to chytridiomycosis is associated with MHC class II conformation. Proc. R. Soc. Lond., Ser. B: Biol. Sci. 282, 20143127.

Berger, L., Speare, R., Hines, H.B., Marantelli, G., Hyatt, A.D., McDonald, K.R., Skerratt, L.F., Olsen, V., Clarke, J.M., Gillespie, G., Mahony, M., Sheppard, N., Williams, C., Tyler, M.J., 2004. Effect of season and temperature on mortality in amphibians due to chytridiomycosis. Aust. Vet. J. 82, 434-439.

Clulow, S., Gould, J., James, H., Stockwell, M., Clulow, J., Mahony, M., 2018. Elevated salinity blocks pathogen transmission and improves host survival from the global amphibian chytrid pandemic: Implications for translocations. J. Appl. Ecol. 55, 830-840.

Gillespie, G., 2010. Population age structure of the spotted tree frog (*Litoria spenceri*): insights into population declines. Wildl. Res. 37, 19-26.

Gillespie, G., Hunter, D., Berger, L., Marantelli, G., 2015. Rapid decline and extinction of a montane frog population in southern Australia follows detection of the amphibian pathogen *Batrachochytrium dendrobatidis*. Anim. Conserv. 18, 295-302.

Grogan, L.F., Phillott, A.D., Scheele, B.C., Berger, L., Cashins, S.D., Bell, S.C., Puschendorf, R., Skerratt, L.F., 2016. Endemicity of chytridiomycosis features pathogen over-dispersion. J. Anim. Ecol. 85, 806–816.

Heard, G.W., Scroggie, M.P., Clemann, N., Ramsey, D.S.L., 2014. Wetland characteristics influence disease risk for a threatened amphibian. Ecol. Appl. 24, 650–662.

Heard, G.W., Scroggie, M.P., Ramsey, D.S., Clemann, N., Hodgson, J.A., Thomas, C.D., 2018. Can habitat management mitigate disease impacts on threatened amphibians? Conserv. Lett. 11, e12375.

Heard, G.W., Thomas, C.D., Hodgson, J.A., Scroggie, M.P., Ramsey, D.S., Clemann, N., 2015. Refugia and connectivity sustain amphibian metapopulations afflicted by disease. Ecol. Lett. 18, 853-863.

Kriger, K.M., Hero, J.M., 2006. Survivorship in wild frogs infected with chytridiomycosis. EcoHealth 3, 171-177.

Kriger, K.M., Hero, J.M., 2007. Large-scale seasonal variation in the prevalence and severity of chytridiomycosis. J. Zool. 271, 352-359.

McDonald, K.R., Mendez, I.D., Muller, R., Freeman, A.B., Speare, R., 2005. Decline in the prevalence of chytridiomycosis in frog populations in North Queensland, Australia. Pac. Conserv. Biol. 11, 114-120.

Murray, K.A., Skerratt, L.F., Garland, S., Kriticos, D., McCallum, H., 2013. Whether the weather drives patterns of endemic amphibian chytridiomycosis: A pathogen proliferation approach. PloS ONE 8, DOI: 10.1371/journal.pone.0061061.

Murray, K.A., Skerratt, L.F., Speare, R., McCallum, H., 2009. Impact and dynamics of disease in species threatened by the amphibian chytrid fungus, *Batrachochytrium dendrobatidis*. Conserv. Biol. 23, 1242-1252.

Newell, D.A., Goldingay, R.L., Brooks, L.O., 2013. Population recovery following decline in an endangered stream-breeding frog (*Mixophyes fleayi*) from subtropical Australia. PloS ONE 8, doi: 10.1371/journal.pone.0058559.

Phillott, A.D., Grogan, L.F., Cashins, S.D., McDonald, K.R., Berger, L., Skerratt, L.F., 2013. Chytridiomycosis and seasonal mortality of tropical stream-associated frogs 15 years after introduction of *Batrachochytrium dendrobatidis*. Conserv. Biol. 27, 1058-1068.

Pickett, E.J., Stockwell, M.P., Bower, D.S., Pollard, C.J., Garnham, J.I., Clulow, J., Mahony, M.J., 2014. Six-year demographic study reveals threat of stochastic extinction for remnant populations of a threatened amphibian. Austral Ecol. 39, 244-253.

Puschendorf, R., Carnaval, A.C., VanDerWal, J., Zumbado-Ulate, H., Chaves, G., Bolanos, F., Alford, R.A., 2009. Distribution models for the amphibian chytrid *Batrachochytrium dendrobatidis* in Costa Rica: proposing climatic refuges as a conservation tool. Divers. Distrib. 15, 401-408.

Puschendorf, R., Hodgson, L., Alford, R.A., Skerratt, L.F., VanDerWal, J., 2013. Underestimated ranges and overlooked refuges from amphibian chytridiomycosis. Divers. Distrib. 19, 1313-1321.

Puschendorf, R., Hoskin, C.J., Cashins, S.D., McDonald, K., Skerratt, L.F., VanDerWal, J., Alford, R.A., 2011. Environmental refuge from disease-driven amphibian extinction. Conserv. Biol. 25, 956-964.

Retallick, R.W.R., McCallum, H., Speare, R., 2004. Endemic infection of the amphibian chytrid fungus in a frog community post-decline. PLoS Biol. 2, 1965-1971.

Rowley, J.J.L., Alford, R.A., 2013. Hot bodies protect amphibians against chytrid infection in nature. Sci. Rep. 3, e1515.

Roznik, E.A., Sapsford, S.J., Pike, D.A., Schwarzkopf, L., Alford, R.A., 2015a. Condition-dependent reproductive effort in frogs infected by a widespread pathogen. Proc. R. Soc. Lond., Ser. B: Biol. Sci. 282, 20150694.

Roznik, E.A., Sapsford, S.J., Pike, D.A., Schwarzkopf, L., Alford, R.A., 2015b. Natural disturbance reduces disease risk in endangered rainforest frog populations. Sci. Rep. 5.

Sapsford, S.J., Alford, R.A., Schwarzkopf, L., 2013. Elevation, temperature, and aquatic connectivity all influence the infection dynamics of the amphibian chytrid fungus in adult frogs. PloS one 8, doi.org/10.1371/journal.pone.0082425.

Sapsford, S.J., Voordouw, M.J., Alford, R.A., Schwarzkopf, L., 2015. Infection dynamics in frog populations with different histories of decline caused by a deadly disease. Oecologia, 1-12.

Scheele, B.C., Hunter, D.A., Banks, S.C., Pierson, J.C., Skerratt, L.F., Webb, R., Driscoll, D.A., 2016. High adult mortality in disease-challenged frog populations increases vulnerability to drought. J. Anim. Ecol. 85, 1453-1460.

Scheele, B.C., Hunter, D.A., Brannelly, L.A., Skerratt, L.F., Driscoll, D.A., 2017a. Reservoir-host amplification of disease impact in an endangered amphibian. Conserv. Biol. 31, 592-600.

Scheele, B.C., Hunter, D.A., Skerratt, L.F., Brannelly, L.A., Driscoll, D.A., 2015. Low impact of chytridiomycosis on frog recruitment enables persistence in refuges despite high adult mortality. Biol. Conserv. 182, 36-43.

Scheele, B.C., Skerratt, L.F., Hunter, D.A., Banks, S.C., Pierson, J.C., Driscoll, D.A., Byrne, P.G., Berger, L., 2017b. Disease-associated change in an amphibian life-history trait. Oecologia 184, 825-833.

Schloegel, L.M., Hero, J.M., Berger, L., Speare, R., McDonald, K., Daszak, P., 2006. The decline of the sharp-snouted day frog (*Taudactylus acutirostris*): The first documented case of extinction by infection in a free-ranging wildlife species? EcoHealth 3, 35-40.

Stevenson, L.A., Roznik, E.A., Alford, R.A., Pike, D.A., 2014. Host-specific thermal profiles affect fitness of a widespread pathogen. Ecology and evolution 4, 4053-4064.

Stockwell, M.P., Bower, D.S., Bainbridge, L., Clulow, J., Mahony, M.J., 2015a. Island provides a pathogen refuge within climatically suitable area. Biodivers. Conserv. 24, 2583-2592.

Stockwell, M.P., Clulow, S., Clulow, J., Mahony, M., 2008. The impact of the amphibian Chytrid Fungus Batrachochytrium dendrobatidis on a Green and Golden Bell Frog Litoria aurea reintroduction program at the Hunter Wetlands Centre Australia in the Hunter Region of NSW. Aust. Zool. 34, 379-386.

Stockwell, M.P., Storrie, L.J., Pollard, C.J., Clulow, J., Mahony, M.J., 2015b. Effects of pond salinization on survival rate of amphibian hosts infected with the chytrid fungus. Conserv. Biol. 29, 391-399.

Valdez, J.W., Stockwell, M.P., Klop-Toker, K., Clulow, S., Clulow, J., Mahony, M.J., 2015. Factors driving the distribution of an endangered amphibian toward an industrial landscape in Australia. Biol. Conserv. 191, 520-528.

Woodhams, D., Ardipradja, K., Alford, R., Marantelli, G., Reinert, L., Rollins-Smith, L., 2007. Resistance to chytridiomycosis varies among amphibian species and is correlated with skin peptide defenses. Anim. Conserv. 10, 409-417.

Woodhams, D.C., Alford, R.A., 2005. Ecology of chytridiomycosis in rainforest stream frog assemblages of tropical Queensland. Conserv. Biol. 19, 1449-1459.

Woodhams, D.C., Rollins-Smith, L.A., Carey, C., Reinert, L., Tyler, M.J., Alford, R.A., 2006. Population trends associated with skin peptide defenses against chytridiomycosis in Australian frogs. Oecologia 146, 531-540.

Europe

Bosch, J., Fernández-Beaskoetxea, S., Garner, T.W., Carrascal, L.M., 2018. Long-term monitoring of an amphibian community after a climate change-and infectious disease-driven species extirpation. Global Change Biol. 24, 2622-2632.

Bosch, J., García-Alonso, D., Fernández-Beaskoetxea, S., Fisher, M.C., Garner, T.W., 2013. Evidence for the introduction of lethal chytridiomycosis affecting wild betic midwife toads (*Alytes dickhilleni*). EcoHealth 10, 82-89.

Bosch, J., Martínez-Solano, I., 2006. Chytrid fungus infection related to unusual mortalities of *Salamandra salamandra* and *Bufo bufo* in the Penalara Natural Park, Spain. Oryx 40, 84-89.

Bosch, J., Martinez-Solano, I., Garcia-Paris, M., 2001. Evidence of a chytrid fungus infection involved in the decline of the common midwife toad (*Alytes obstetricans*) in protected areas of central Spain. Biol. Conserv. 97, 331-337.

Bosch, J., Rincon, P.A., 2008. Chytridiomycosis-mediated expansion of Bufo bufo in a montane area of Central Spain: an indirect effect of the disease. Divers. Distrib. 14, 637-643.

Doddington, B.J., Bosch, J., Oliver, J.A., Grassly, N.C., Garcia, G., Schmidt, B.R., Garner, T.W.J., Fisher, M.C., 2013. Context-dependent amphibian host population response to an invading pathogen. Ecology 94, 1795-1804.

Martínez-Solano, I., Bosch, J., García-París, M., 2003. Demographic trends and community stability in a montane amphibian assemblage. Conserv. Biol. 17, 238-244.

Rosa, G., Anza, I., Moreira, P., Conde, J., Martins, F., Fisher, M., Bosch, J., 2013. Evidence of chytrid-mediated population declines in common midwife toad in Serra da Estrela, Portugal. Anim. Conserv. 16, 306-315.

Tobler, U., Borgula, A., Schmidt, B.R., 2012. Populations of a susceptible amphibian species can grow despite the presence of a pathogenic chytrid fungus. PLoS ONE 7, doi.org/10.1371/journal.pone.0034667.

Walker, S.F., Bosch, J., Gomez, V., Garner, T.W.J., Cunningham, A.A., Schmeller, D.S., Ninyerola, M., Henk, D.A., Ginestet, C., Arthur, C.P., Fisher, M.C., 2010. Factors driving pathogenicity vs. prevalence of amphibian panzootic chytridiomycosis in Iberia. Ecol. Lett. 13, 372-382.

Central America

Becker, C.G., Zamudio, K.R., 2011. Tropical amphibian populations experience higher disease risk in natural habitats. Proc. Natl. Acad. Sci. USA 108, 9893-9898.

Bustamante, H.M., Livo, L.J., Carey, C., 2010. Effects of temperature and hydric environment on survival of the Panamanian Golden Frog infected with a pathogenic chytrid fungus. Integrative Zoology 5, 143-153.

Cheng, T.L., Rovito, S.M., Wake, D.B., Vredenburg, V.T., 2011. Coincident mass extirpation of neotropical amphibians with the emergence of the infectious fungal pathogen *Batrachochytrium dendrobatidis*. Proc. Natl. Acad. Sci. USA 108, 9502-9507.

Crawford, A.J., Lips, K.R., Bermingham, E., 2010. Epidemic disease decimates amphibian abundance, species diversity, and evolutionary history in the highlands of central Panama. Proc. Natl. Acad. Sci. USA 107, 13777-13782.

García-Rodríguez, A., Chaves, G., Benavides-Varela, C., Puschendorf, R., 2012. Where are the survivors? Tracking relictual populations of endangered frogs in Costa Rica. Divers. Distrib. 18, 204-212.

La Marca, E., Lips, K.R., Lotters, S., Puschendorf, R., Ibanez, R., Rueda-Almonacid, J.V., Schulte, R., Marty, C., Castro, F., Manzanilla-Puppo, J., Garcia-Perez, J.E., Bolanos, F., Chaves, G., Pounds, J.A., Toral, E., Young, B.E., 2005. Catastrophic population declines and extinctions in neotropical harlequin frogs (Bufonidae: Atelopus). Biotropica 37, 190-201.

Lips, K.R., 1998. Decline of a tropical montane amphibian fauna. Conserv. Biol. 12, 106-117.

Lips, K.R., Brem, F., Brenes, R., Reeve, J.D., Alford, R.A., Voyles, J., Carey, C., Livo, L., Pessier, A.P., Collins, J.P., 2006. Emerging infectious disease and the loss of biodiversity in a Neotropical amphibian community. Proc. Natl. Acad. Sci. USA 103, 3165-3170.

Lips, K.R., Burrowes, P.A., Mendelson III, J.R., Parra-Olea, G., 2005. Amphibian declines in Latin America: Widespread population declines, extinctions, and impacts. Biotropica 37, 163-165.

Lips, K.R., Reeve, J.D., Witters, L.R., 2003. Ecological traits predicting amphibian population declines in Central America. Conserv. Biol. 17, 1078-1088.

Lotters, S., Kielgast, J., Bielby, J., Schmidtlein, S., Bosch, J., Veith, M., Walker, S.F., Fisher, M.C., Rodder, D., 2009. The link between rapid enigmatic amphibian decline and the globally emerging chytrid fungus. EcoHealth 6, 358-372.

McCaffery, R., Lips, K., 2013. Survival and abundance in males of the glass frog Espadarana (Centrolene) prosoblepon in central Panama. J. Herpetol. 47, 162-168.

McCaffery, R., Richards-Zawacki, C.L., Lips, K.R., 2015. The demography of Atelopus decline: Harlequin frog survival and abundance in central Panama prior to and during a disease outbreak. Global Ecology and Conservation 4, 232-242.

Puschendorf, R., Bolanos, F., Chaves, G., 2006. The amphibian chytrid fungus along an altitudinal transect before the first reported declines in Costa Rica. Biol. Conserv. 132, 136-142.

Puschendorf, R., Carnaval, A.C., VanDerWal, J., Zumbado-Ulate, H., Chaves, G., Bolanos, F., Alford, R.A., 2009. Distribution models for the amphibian chytrid *Batrachochytrium dendrobatidis* in Costa Rica: proposing climatic refuges as a conservation tool. Divers. Distrib. 15, 401-408.

Richards-Zawacki, C.L., 2010. Thermoregulatory behaviour affects prevalence of chytrid fungal infection in a wild population of Panamanian golden frogs. Proc. R. Soc. Lond., Ser. B: Biol. Sci. 277, 519-528.

Savage, A.E., Zamudio, K.R., 2016. Adaptive tolerance to a pathogenic fungus drives major histocompatibility complex evolution in natural amphibian populations. Proc. R. Soc. B 283, 20153115.

Tarvin, R.D., Peña, P., Ron, S.R., 2014. Changes in population size and survival in Atelopus spumarius (Anura: Bufonidae) are not correlated with chytrid prevalence. J. Herpetol. 48, 291-297.

Voyles, J., Woodhams, D.C., Saenz, V., Byrne, A.Q., Perez, R., Rios-Sotelo, G., Ryan, M.J., Bletz, M.C., Sobell, F.A., McLetchie, S., 2018. Shifts in disease dynamics in a tropical amphibian assemblage are not due to pathogen attenuation. Science 359, 1517-1519.

Woodhams, D.C., Kilburn, V.L., Reinert, L.K., Voyles, J., Medina, D., Ibánez, R., Hyatt, A.D., Boyle, D.G., Pask, J.D., Green, D.M., 2008. Chytridiomycosis and amphibian population declines continue to spread eastward in Panama. EcoHealth 5, 268-274.

North America

Andre, S.E., Parker, J., Briggs, C.J., 2008. Effect of temperature on host response to *Batrachochytrium dendrobatidis* infection in the mountain yellow-legged frog (*Rana muscosa*). J. Wildl. Dis. 44, 716-720.

Beyer, S.E., Phillips, C.A., Schooley, R.L., 2015. Canopy cover and drought influence the landscape epidemiology of an amphibian chytrid fungus. Ecosphere 6, 1-18.

Briggs, C.J., Knapp, R.A., Vredenburg, V.T., 2010. Enzootic and epizootic dynamics of the chytrid fungal pathogen of amphibians. Proc. Natl. Acad. Sci. USA 107, 9695-9700.

Briggs, C.J., Vredenburg, V.T., Knapp, R.A., Rachowicz, L.J., 2005. Investigating the population-level effects of chytridiomycosis: An emerging infectious disease of amphibians. Ecology 86, 3149-3159.

Forrest, M.J., Edwards, M.S., Rivera, R., Sjoeberg, J.C., Jaeger, J., 2015. High prevalence and seasonal persistence of amphibian chytrid fungus infections in the desert-dwelling Amargosa Toad, *Anaxyrus nelsoni*. Herpetological Conservation and Biology 10, 917-925.

Forrest, M.J., Schlaepfer, M.A., 2011. Nothing a hot bath won't cure: Infection rates of amphibian chytrid fungus correlate negatively with water temperature under natural field settings. PLoS ONE 6, doi: 10.1371/journal.pone.0028444.

Gervasi, S.S., Stephens, P.R., Hua, J., Searle, C.L., Xie, G.Y., Urbina, J., Olson, D.H., Bancroft, B.A., Weis, V., Hammond, J.I., 2017. Linking ecology and epidemiology to understand predictors of multi-host responses to an emerging pathogen, the amphibian chytrid fungus. PloS one 12, e0167882.

Howell, P.E., Hossack, B.R., Muths, E., Sigafus, B.H., Chandler, R.B., 2016. Survival estimates for reintroduced populations of the Chiricahua leopard frog (*Lithobates chiricahuensis*). Copeia 104, 824-830.

Kinney, V.C., Heemeyer, J.L., Pessier, A.P., Lannoo, M.J., 2011. Seasonal pattern of *Batrachochytrium dendrobatidis* infection and mortality in *Lithobates areolatus*: affirmation of Vredenburg's "10,000 Zoospore Rule". PLoS ONE 6, e16708.

Knapp, R.A., Fellers, G.M., Kleeman, P.M., Miller, D.A., Vredenburg, V.T., Rosenblum, E.B., Briggs, C.J., 2016. Large-scale recovery of an endangered amphibian despite ongoing exposure to multiple stressors. Proc. Natl. Acad. Sci. USA 113, 11889-11894.

Lambert, B.A., Schorr, R.A., Schneider, S.C., Muths, E., 2016. Influence of demography and environment on persistence in toad populations. The Journal of Wildlife Management 80, 1256-1266.

Mosher, B.A., Bailey, L.L., Muths, E., Huyvaert, K.P., 2018. Host-pathogen metapopulation dynamics suggest high elevation refugia for boreal toads. Ecol. Appl. 28, 926-937.

Muths, E., Corn, P.S., Pessier, A.P., Green, D.E., 2003. Evidence for disease-related amphibian decline in Colorado. Biol. Conserv. 110, 357-365.

Muths, E., Scherer, R.D., Pilliod, D.S., 2011. Compensatory effects of recruitment and survival when amphibian populations are perturbed by disease. J. Appl. Ecol. 48, 873-879.

Pilliod, D.S., Muths, E., Scherer, R.D., Bartelt, P.E., Corn, P.S., Hossack, B.R., Lambert, B.A., McCaffery, R., Gaughan, C., 2010. Effects of amphibian chytrid fungus on individual survival probability in wild boreal toads. Conserv. Biol. 24, 1259-1267.

Savage, A.E., Sredl, M.J., Zamudio, K.R., 2011. Disease dynamics vary spatially and temporally in a North American amphibian. Biol. Conserv. 144, 1910-1915.

Savage, A.E., Zamudio, K.R., 2011. MHC genotypes associate with resistance to a frog-killing fungus. Proc. Natl. Acad. Sci. USA 108, 16705-16710.

Savage, A.E., Zamudio, K.R., 2016. Adaptive tolerance to a pathogenic fungus drives major histocompatibility complex evolution in natural amphibian populations. Proc. R. Soc. B 283, 20153115.

Vredenburg, V.T., Knapp, R.A., Tunstall, T.S., Briggs, C.J., 2010. Dynamics of an emerging disease drive large-scale amphibian population extinctions. Proc. Natl. Acad. Sci. USA 107, 9689-9694.

South America

Becker, C.G., Zamudio, K.R., 2011. Tropical amphibian populations experience higher disease risk in natural habitats. Proc. Natl. Acad. Sci. USA 108, 9893-9898.

Catenazzi, A., Lehr, E., Rodriguez, L.O., Vredenburg, V.T., 2011. *Batrachochytrium dendrobatidis* and the collapse of anuran species richness and abundance in the Upper Manu National Park, southeastern Peru. Conserv. Biol. 25, 382-391.

Catenazzi, A., Lehr, E., Vredenburg, V.T., 2014. Thermal physiology, disease, and amphibian declines on the eastern slopes of the Andes. Conserv. Biol. 28, 509-517.

Catenazzi, A., von May, R., Vredenburg, V.T., 2013. High prevalence of infection in tadpoles increases vulnerability to fungal pathogen in high-Andean amphibians. Biol. Conserv. 159, 413-421.

Louca, S., Lampo, M., Doebeli, M., 2014. Assessing host extinction risk following exposure to *Batrachochytrium dendrobatidis*. Proc. R. Soc. Lond. B Biol. Sci. 281, 20132783.

Soto-Azat, C., Valenzuela-Sánchez, A., Clarke, B.T., Busse, K., Ortiz, J.C., Barrientos, C., Cunningham, A.A., 2013a. Is chytridiomycosis driving Darwin's frogs to extinction? PLoS one 8, e79862.

Soto-Azat, C., Valenzuela-Sánchez, A., Collen, B., Rowcliffe, J.M., Veloso, A., Cunningham, A.A., 2013b. The population decline and extinction of Darwin's frogs. PLoS one 8, e66957.

Valenzuela-Sánchez, A., Schmidt, B.R., Uribe-Rivera, D.E., Costas, F., Cunningham, A.A., Soto-Azat, C., 2017. Cryptic disease-induced mortality may cause host extinction in an apparently stable host–parasite system. Proc. R. Soc. B 284, 20171176.