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Synthesis

Facilitating evolutionary rescue from a wildlife health threat with cross-sectoral strategies: a case study on white-nose syndrome

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ABSTRACT. Evolutionary rescue, the ability of a species to evolve under new selective pressures and rebound from threats, occurs within a social-ecological system. Evolutionary rescue may help wildlife populations persist in the face of extinction threats such as emerging infectious diseases, which are often caused or exacerbated by human activities and are inherently difficult to manage. Effective management of wildlife health often relies upon changing human behavior, and underlying values and social norms. Thus, managing wildlife health requires collaborative, diverse approaches that recognize the complex social-ecological context in which they occur and seek to optimize outcomes for wildlife and human health while improving resiliency of species and ecosystems (i.e., a One Health framework). We pull from our experience with white-nose syndrome, a highly lethal disease of multiple hibernating bat species in North America, to highlight cross-sectoral management strategies that could directly support evolutionary rescue of populations imperiled by disease. We explain how such strategies can buttress or enhance the natural trajectory of evolutionary rescue, providing alternatives to approaches that are reactive and crisis-oriented. Facilitation of evolutionary rescue represents a potential long-term conservation strategy, but the very nature of social-ecological systems means there are significant uncertainties and risks regarding feasibility and outcomes across different contexts. We suggest several proactive strategies to support evolutionary rescue where applicable, including communication and outreach to build public awareness and involvement, policies tailored for conservation and potential recovery, and basic ecological research to support conservation decisions. These highly active, "do more" strategies to promote wildlife health should not be conflated with a laissez-faire management response. Indeed, active management to support the recovery of imperiled bat populations is critical to ensuring their persistence, and the realistic and feasible options we summarize here can substantially reduce long-term extinction risk. We recommend greater cross-sectoral wildlife health investments to capitalize on the power of human-nature partnerships in facilitating evolutionary rescue as a key consideration in conservation of imperiled species.

Key Words: *bats; chiroptera; conservation; disease; epizootic; evolutionary rescue; extinction; health; invasive species; One Health; resilience; wildlife*

INTRODUCTION

Wildlife health is a global concern and an important barometer of disrupted relationships among people, wildlife, livestock, and ecosystems (Stephen 2014, Walzer 2017). Not surprisingly, threats of disease to both biodiversity and human health increase with intensified anthropogenic alteration of the environment (Daszak et al. 2000, Tompkins et al. 2015, Cunningham et al. 2017). For instance, the global commercial trade in amphibians facilitated the spread of fungal pathogens that cause chytridiomycosis, which now affects > 500 species of frogs and salamanders and may be further exacerbated by climate change (Greenspan et al. 2017). Chytridiomycosis has resulted in 90–100% mortality in some affected populations and presumed extinctions of 90 species (Martel et al. 2013, Scheel et al. 2019). Human-mediated spread of African swine fever virus from domestic pigs now threatens 11 wild endemic pig species in Southeast Asia with extinction (Luskin et al. 2021). In contrast, limiting human impacts and retaining intact wildlife communities can reduce disease risk in some cases (Eby et al. 2023). For example, human risk of contracting Lyme disease is lower in areas with high richness of mammalian wildlife host species (Halsey and Miller 2020; Keesing and Ostfeld 2021).

Responses to wildlife health threats tend to rely on reactive strategies used for managing livestock or human diseases, such as "test, isolate, cull" (in the case of livestock) or treat, but these may be ineffective or impossible to scale up for free-ranging wildlife populations (Streicker et al. 2012, Wolfe et al. 2018, CMS FAO 2022). Alternative management strategies that focus on prevention and resilience may be more effective mitigation for these threats (Allen et al. 2011).

Fortunately, such prevention-oriented strategies are often the least costly first line of defense against wildlife disease threats. These include minimizing the potential spread of known pathogens to "naive" animal populations, or enhancing resilience of host populations. For example, a recent ban on importation of

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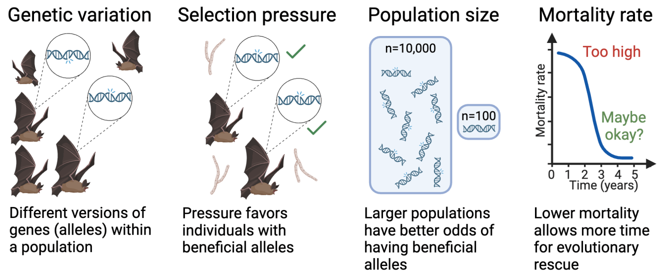
200 amphibian species into the U.S. was implemented to protect the nation's high salamander biodiversity from introduction of a lethal salamander chytrid fungus (USFWS 2016). However, preventing pathogen introductions or disease emergence is not always successful nor possible, especially given the global rapid increase in emerging diseases and trade, the complex effects of climate change and anthropogenic factors on disease emergence, and the lack of investment by governments in proactive and coherent strategies (Bloom and Cadarette 2019). Successful wildlife conservation often requires a holistic approach, recognizing that disease is just one of many pressures that populations face. Strategies that improve resilience of populations prior to disease emergence, or a multitude of other threats, are likely to bolster natural recovery of populations following something like an epizootic (Allen et al. 2011). Resilience in this context operates at the individual and population level and describes the capacity to adapt and return to a reference state following perturbation by a specific threat or threats, resulting in recovery of that individual or population.

Biologically, evolutionary rescue is the result of selection of heritable traits (e.g., physiological, immunological, behavioral) that occurs quickly enough for a population to adapt to a novel stressor and recover from a decline (Fig. 1; Gonzalez et al. 2013). This recovery is not the result of immigration, rather of selection for beneficial phenotypes from the existing variation in a population (Carlson et al. 2014). Paradoxically, there is a well-developed field of research on factors that promote evolutionary rescue of pathogens, including antimicrobial drug resistant bacteria, cancer cells, and viruses within hosts (Alexander et al. 2014). In these organisms, the probability of rescue increases with initial population size, standing genetic variation, and gene dispersal, and decreases with stressful environments and rapid rates of exposure to the stressor (Carlson et al. 2014, Lachapelle et al. 2017).

Although biological principles provide the foundation for evolutionary rescue, practical application requires navigating complex social, economic, and policy landscapes that can either facilitate or constrain evolutionary processes. In fact, without social-ecological factors being considered, evolutionary rescue can be unattainable.

Published reports of evolutionary rescue in animals remain limited with scientific investigations of evolutionary rescue systems largely focused on those with human health, agricultural, or economic importance. The best known example of evolutionary rescue from a disease threat in vertebrates is the evolution of resistance to myxoma virus (genus *Leporipoxvirus*) among invasive European rabbits (*Oryctolagus cuniculus*) in Australia. The release of a rabbit virus in Australia triggered a co-evolutionary arms race, with the virus becoming less deadly and the rabbits developing resistance, both favoring a stable host-pathogen dynamic (Kerr et al. 2015). Similarly, rodents developed resistance to warfarin, an anticoagulant rodenticide, through genetic mutations in rodents that appear to affect blood clotting (Pelz et al. 2005, Vander Wal et al. 2013). Populations of rainbow trout (*Onchorynchus mykiss*) in Montana, USA, rebounded following a significant decline caused by a European parasite (*Myxobolus cerebralis*) that causes whirling disease (Miller and

Fig. 1. Key elements of evolutionary rescue include genetic variation, selection pressure (the Y shape represents fungal hyphae growing on the bat skin), population size, and mortality rate. Human and management actions can influence these elements through avoiding extirpations, regulating the intensity of the selection pressures, maintenance of large populations, and slowing population declines associated with the stressor (created with https://www.biorender.com/).



Vincent 2008). Similarly, male field crickets (*Teleogryllus oceanicus*) on Kaua'i, Hawai'i, evolved silent wings associated with mutations in a single gene, following introduction of a parasitic fly (*Ormia ochracea*) that uses sound to locate its host (Zuk et al. 2006). Field observations and modeling suggest evolutionary rescue may also be underway in some amphibian populations impacted by chytridiomycosis (Christie and Searle 2018, DiRenzo et al. 2018). For wildlife diseases with negligible economic importance or direct impacts on human health, or for which direct interventions are costly or unavailable, evolutionary rescue may provide an alternative intervention.

Strategies that increase the probability of evolutionary rescue present potential long-term solutions to both existing and future wildlife health threats. Technologies designed to improve survival of animals exposed to a pathogen, such as vaccination, can provide targeted short-term control of novel diseases, and may also facilitate development of resistance or tolerance by providing more time for host adaptation (i.e., slow the rate of population decline; Fig. 1). In the absence of available technologies for direct disease prevention or treatment, other strategies may be designed to strengthen a species' or population's resilience or adaptive capacity. For example, minimizing other sources of mortality or reduced recruitment can help to maintain or increase population size, which increases the probability of persistence for beneficial alleles, and reduces extirpation or extinction risks from stochastic events. Retaining and enhancing quality habitat and minimizing other stressors can help bolster individuals' capacity to cope with current pathogens, and provides the space and necessary resources for recolonization or recovery of populations that may locally disappear for a time.

Using white-nose syndrome (WNS), a disease of hibernating bats (Blehert et al. 2009, Hoyt et al. 2021), we illustrate how coordinated, cross-sectoral strategies can positively influence the social-ecological trajectory of evolutionary rescue (Fig. 2). We emphasize that although evolutionary rescue can occur without human intervention, a management approach that promotes evolutionary rescue is not a passive, "do less" approach. Instead,

Fig. 2. Enabling social conditions and targeted steps essential to supporting evolutionary rescue. Heritable traits associated with increased population growth (i.e., phenotypes that confer increased fitness) vary as selective pressures change, for example, with climate change and introduction of novel pathogens. Therefore, an adaptive management approach is essential, through which evaluation of actions taken to support evolutionary rescue (Targeted Step 4) informs the subsequent round of actions (Steps 1-3).

management to facilitate evolutionary rescue requires active protection of target populations to build resilience and support recovery. We explain how "do more" strategies to support the health of threatened species include effective science communication and outreach to engage the public in conservation, development, and implementation of more proactive policies for conservation and recovery, investments in applied ecological research and monitoring, and cross-sector collaborations that facilitate application of scientific knowledge and a broad ecosystem approach to conservation.

WHITE-NOSE SYNDROME AND EVOLUTIONARY RESCUE

WNS is a devastating wildlife disease driven by a complex interplay among hibernation environment, behavior, and physiology of the host, and growth and physiology of the pathogen (Hoyt et al. 2021). First detected in New York in 2006 (Blehert et al. 2009), the fungal pathogen *Pseudogymnoascus destructans* has spread to the majority of U.S. states and Canadian provinces with new detections reported each year (https://www.whitenosesyndrome.org). Within the first two years of its discovery in North America, populations of six hibernating bat species experienced average population declines of 88% and several studies have projected species extinctions as an outcome of WNS (Frick et al. 2010, 2015, Turner et al. 2011, Langwig et al. 2012, Maslo et al. 2015, Cheng et al. 2021). Three North American bat species that experienced significant widespread declines, little brown myotis (*Myotis lucifugus*), northern long-eared myotis (*Myotis septentrionalis*), and tricolored bats (*Perimyotis subflavus*), have been proposed for, or received, endangered species protections in the U.S. or Canada (COSEWIC 2013, Environment and Climate Change Canada 2018, USFWS 2022a, USFWS 2022b).

The pathophysiology of WNS is initiated by fungal invasion of the epidermis and underlying connective tissue of the wing membranes of bats during hibernation. In susceptible individuals, severe damage to the wing results in disruptions of physiology, altered hibernation behavior, and immune responses that affect disease outcomes (Warnecke et al. 2012, 2013, Verant et al. 2014, Mayberry et al. 2018, Hoyt et al. 2021). Most of what is known about the pathophysiology of WNS is from laboratory studies on little brown myotis, although a few studies have experimentally infected other species (Davy et al. 2017a, 2020, Moore et al. 2018, Verant et al. 2018, Frick et al. 2022). Mortality in highly susceptible individuals occurs during hibernation or shortly after spring emergence because of disruptions of homeostasis, including increased energy expenditure and water loss (Reeder et al. 2012, McGuire et al. 2017). Systemic inflammatory responses to the fungal infection at the time of spring emergence can also exacerbate wing damage and contribute to mortality even if a bat survives the winter (Meteyer et al. 2012, Fuller et al. 2020). The disruption of water balance results in dehydration and electrolyte imbalances, which may trigger more frequent energy-consuming arousals and flights related to thirst, resulting in a faster depletion of overwintering fat stores (Thomas and Cloutier 1992, Cryan et al. 2010, Willis et al. 2011, McGuire et al. 2017).

Fungal load, hibernation ecophysiology, microclimate roosting preferences, and type of immune response appear to contribute to variation in WNS impacts among species, populations, and individuals (Langwig et al. 2012, 2016, Bernard et al. 2020, Davy et al. 2020, Hoyt et al. 2021, Grimaudo et al. 2022). Species with naturally high rates of water loss, including tricolored bats, little brown myotis, fringed myotis (*Myotis thysanodes*), long-legged myotis (*Myotis volans*), and long-eared myotis (*Myotis evotis*; McGuire et al. 2021) appear to preferentially select roost sites with high humidity, where the fungus also grows well (Boyles et al. 2022, Haase et al. 2021).

Several tech-based interventions are being investigated, and are in various stages of development from laboratory to field trials. These include direct treatment of bats (e.g., with antifungal agents, probiotics, UV light, and vaccination), and decontamination of hibernacula and other important roost sites where the fungus can persist (e.g., antifungal agents, disinfectants, UV light; Cornelison et al. 2014, Hoyt et al. 2019, 2023, Rocke et al. 2019, Sewall et al. 2023). Targets to reduce fungal virulence are also being investigated (Reeder et al. 2017, Thapa et al 2022). Other methods have focused on physically changing the environment of sites where bats hibernate to make them less suitable for *P. destructans* and support bat survival over winter (Turner et al. 2022, Boyles et al. 2023, Sewall et al. 2023). Although there have been promising results from these interventions, there is sufficient variation among species, populations, and locations to limit application of these strategies as sole solutions, or to scale them up across large geographic areas. Additionally, the high cost of applying treatments, the potential for impacts to non-target organisms, and competition with other management objectives can create barriers to implementation (Hallam and McCracken 2011, Hoyt et al. 2019, Fletcher et al. 2020, Grider et al. 2022). On their own, such strategies are not suited to "forever" time horizons (Fletcher et al. 2020, Grider et al. 2022), requiring annual treatments that are resource intensive and difficult to scale to an entire population or species. However, temporary and targeted interventions during the epidemic phase could reduce mortality or reproductive losses during this time period, allowing more time and opportunity for evolutionary rescue to occur.

An underlying biological requirement of evolutionary rescue is that the population contains sufficient genetic diversity that some proportion of individuals have or will obtain a genotype that produces a phenotype conferring greater fitness under the new selective pressure causing the population to decline (Fig. 1; Donaldson et al. 2017). For example, WNS has exerted selection on genes associated with arousals from torpor, fat acquisition and metabolism, and vocalizations in little brown myotis that survived the initial mass mortality caused by WNS (Auteri and Knowles 2020). Changes in arousal frequency have been associated with increased late-winter fat stores and reduced mortality from WNS (Frank et al. 2019). Cheng et al. (2019) observed a phenotypic shift in pre-hibernation fat stores for little brown myotis from some (though not all) hibernacula in the eastern U.S. with persisting bats at some sites storing more pre-hibernation fat, on average, than bats did before WNS. Importantly, these genotypic and phenotypic changes appear to be correlated with effects on population growth. A study of two little brown myotis populations recovering from WNS found evidence of genetic selection at multiple loci, including one locus in an immune gene (Gignoux-Wolfsohn et al. 2021). Evidence of reduced fungal loads in persisting populations of little brown myotis in the eastern U.S., where WNS is now considered endemic, suggests that bats have developed resistance to infection in some areas (Langwig et al. 2012, 2017). Annual surveys of some little brown myotis populations that originally experienced WNS losses exceeding 75% now appear to be stabilizing or slightly increasing (Dobony and Johnson 2018, Frank et al. 2019, Cheng et al. 2021, Hooton et al. 2023).

Although there are promising indicators of adaptation to WNS in some little brown myotis bat populations in North America, it is still too early to conclude whether evolutionary rescue will enable long-term persistence of affected populations or other species. Notably, the biological conditions for evolutionary rescue are inseparable from eco-evolutionary and social processes that shape whether a population contains sufficient genetic diversity for evolutionary rescue. Any number of social influences, including climate change, fragmentation, and agriculture expansion are constantly interacting with eco-evolutionary dynamics, influencing selection processes and genotypes (Hendry et al. 2017). WNS has caused severe bottlenecks in some bat populations (Langwig et al. 2012, Frick et al. 2015, Lilley et al. 2016) reducing overall genetic diversity of the affected species. These bottlenecks leave persisting, small populations extremely vulnerable to stochastic events and additional novel threats. Yet, modeling suggests that some remnant populations may still be sufficiently large and contain sufficient genetic diversity to facilitate evolutionary rescue, despite WNS and other stressors (Bell 2017, Maslo and Fefferman 2015, Frank et al. 2019).

Documenting evolutionary rescue is especially challenging in small, remnant populations because nascent signals of rescue could be difficult to detect and adaptations to survive WNS may not be occurring in all populations or species (Hopkins et al. 2021). Moreover, not all observed changes in genotype and trait frequency from directional selection will benefit populations. Although the apparent recovery of some eastern populations from the bottleneck caused by WNS is encouraging, there is no certainty that the same outcome will occur in other regions where bats have been subject to potentially different selective pressures.

SETTING THE STAGE FOR SUCCESSFUL EVOLUTIONARY RESCUE

Integrating evolutionary rescue effectively with conservation and recovery planning for species threatened by disease requires substantial forethought and long-term investments at different scales (Table 1). In 2011 the U.S. Fish and Wildlife Service and later the Canadian Wildlife Health Cooperative (supported by Environment and Climate Change Canada) led collaborative development of national WNS plans (Coleman et al. 2011, CWHC 2021). These contained One Health elements in practice, though not named as such, which create frameworks to coordinate response actions by federal, state, provincial, territorial, local, and Indigenous (i.e., multi-jurisdictional) partners. Importantly, these approaches were cross-sectoral, including non-government scientific, nonprofit, and public actors (i.e., cross-sectoral; Coleman et al. 2011, ECCC 2018). The goals and scope of activities within these plans were also holistic. For example, the U.S. plan included the following seven elements: (1) communications and outreach, inclusive of outreach to "non-government research scientists and institutions, non-government organizations, elected officials (State and Federal), private land managers, decision makers, private industry, relevant stakeholders, news media, and the public" (Coleman et al. 2011:8); (2) data and technical information management, to develop a central repository for national assessments and specific projects that are central to monitoring populations; (3) diagnostic, to develop standards and coordinate diagnostics across labs; (4) disease management, to mobilize researchers and managers to mitigate disease impacts and spread; (5) epidemiological and ecological research, to investigate both bat and pathogen ecology as well as disease impacts to inform and prioritize management decisions; (6) disease surveillance, to enable early detection of the fungus and the disease in new areas and new species; and (7) conservation and recovery, to assess vulnerability, prioritize traditional conservation actions, and develop guidelines for maintaining or recovering bat populations affected by WNS (Coleman et al. 2011).

Core to both plans is the generation of knowledge through basic and applied research to inform management strategies. Although research itself does not result in species recovery, integration of research into conservation projects is essential to ensuring an evidence-based approach to decision making, and to an adaptive management framework that allows the outcomes of conservation interventions to be evaluated and improved where possible (Bennett et al. 2017, Christie et al. 2022). In addition to research and management targets, these response plans elevate coordinated conservation and communication strategies for WNS and other stressors on bat health and conservation by reaching policy makers, land managers, and the public, a de facto One Health approach.

Table 1. Key objectives to facilitate the evolutionary rescue of declining species from local to range-wide scales with specific examples of activities to help bats survive white-nose syndrome (WNS) and other threats. A range of actors are required to support these activities, including scientists, conservation practitioners, Indigenous communities and organizations, public sector workers and policy makers, private for profit and non-profit sector actors, and the general public.

Key objectives	Activity (at local to range-wide scales)
Habitat protection	Protect known hibernacula, hibernation areas (e.g., caves, mines, talus slopes, forest stands), and significant maternity sites (e.g., old growth/mature forest stands) from destruction or degradation.
	Support land-use planning processes at multiple jurisdictional levels (municipal, county, state/provincial/territory, and federal) to identify and protect important bat habitat from development for housing, roads, and other infrastructure.
	Identify and report important bat habitat to jurisdictional agencies tasked with managing bat populations and habitat. Roost locations, data on monitoring of roosts, and identification of migration corridors through capture or acoustics should be submitted to North American Bat Monitoring Program (NABat).
	Pass and enforce federal, state/provincial/territorial, and Indigenous regulatory protections for important habitat, and create transboundary agreements to ensure cohesive conservation legislation.
Protection of food resources	Protect habitats required to support healthy insect populations that provide prey for bats.
	Investigate if reduced pesticide use benefits bat populations, and if bat populations are limited by prey availability. Biocides used for mosquito control have been shown to substantially reduce non-target midges (Allgeier et al. 2019), which can comprise more than 80% of some bats' diets (summarized in Brühl et al. 2020).
	Examine how pesticides and other chemicals may affect bat health directly.
Improved understanding of species ecology and threats faced	Support research on bat ecology, effects of WNS, co-infections with WNS and other pathogens, and non-WNS threats (e.g., climate change, habitat loss and degradation), to inform adaptive management of recovering bat populations.
	Through permitting, require submission of acoustics and carcass data to NABat, and submission of carcasses to state/provincial repositories.
	Research physiological, morphological, biochemical traits that may influence susceptibility to WNS or other threats.
	Establish standardized case definitions and diagnostic protocols for pathogen detection and disease diagnosis.
	Ensure long-term plans for conservation interventions will support evolutionary rescue rather than diluting the selective pressure of WNS or other emerging threats to which the population must adapt.
	Engage the public in programs to collect bat observations, and develop and distribute education resources, including resources on humane exclusion of nuisance bats in buildings.
	Monitor high-risk species for indications of adaptation to WNS and survey for disease; contribute data to the North American Bat Monitoring Program to determine local to range-wide population status and trends from summer acoustic data and winter colony counts.
	Communicate the science clearly and effectively to a range of audiences, to ensure that the most current available scientific knowledge is available to inform the decisions of policy makers, wildlife managers, and the public.
	Understand the role of multiple stressors (e.g., climate change, habitat loss, co-infections) in the survival and reproduction of bats.
Reduction of additional mortality	When removing nuisance bats from human-made structures ensure suitable alternate roost habitat is available in the immediate area; if not already codified, use non-lethal exclusionary measures; make necessary exceptions for cases of rabies exposure. If excluding a maternity colony, time the exclusion to avoid the maternity season.
	Limit populations of feral and outdoor domestic cats to relieve predation pressure on wildlife.
	Through permitting, require an exploratory process and due diligence to site wind turbines out of bat migration routes.
	Require implementation of proven strategies to reduce bat mortality at wind turbines (e.g., blanket curtailment where turbines do not operate from dusk to dawn during migration periods and at low wind-speeds, or employ smart curtailment where turbine operations reflect high versus low mortality risk conditions).
	Protect known hibernacula and hibernation areas (e.g., caves, mines, talus slopes, forest stands) from excess human disturbance during winter, including disturbance from recreational activities.
	Pass and enforce federal, state/provincial/territorial, and Indigenous regulatory protections; e.g., list species on the U.S. Endangered Species Act to limit any additional take of individuals from populations at risk of extinction, and create transboundary agreements to ensure cohesive conservation legislation.
Technological advancements	Work to advance bat deterrents at wind energy facilities and tailings ponds to reduce mortality.

Evolutionary rescue was not an explicit strategy in national WNS plans, but elements of these plans and actions have laid the foundation for evolutionary rescue. When socially enabling (e.g., a One Health approach) and biologically enabling (e.g., heritable traits are present that impart greater ability to survive the stressor) conditions are in place, evolutionary rescue can also be promoted with more targeted steps (Fig. 2, Steps 1–4). Here actions that maximize population size and spatial heterogeneity will maintain the highest possible genetic diversity, and therefore the greatest adaptive potential of the species to present and future threats (Step 1). A broad suite of actions are available here, from traditional species protection laws to development and promotion of best management practices that enhance survival and reproduction, and minimize mortality from known stressors.

More targeted disease interventions may also be necessary when the intensity of a selective stressor and mortality rate is too high to allow for adaptation to occur or when the presence of biological enabling conditions for evolutionary rescue are uncertain. As described earlier, these targeted interventions may be applied just during the epidemic phase or longer in the absence of apparent resistance or tolerance to the disease. For example, vaccination of little brown myotis is most effective at increasing survival rates within the first few years of WNS emergence in the population, but does not provide the same survival advantage in bats where WNS has been established for several years (USGS 2023). In contrast, longer-term vaccination of northern long-eared myotis may be required to prevent extirpation of the species because of persistent population declines across the majority of its range (Hoyt et al. 2021). In general, interventions that prevent infection and inhibit development of tolerance or resistance should be used with caution. Once that intervention is no longer applied, the treated population will be "naive" to infection and suffer high mortality rates again.

Interventions will have longer-lasting effects if they support individuals with heritable traits associated with survival and reproduction under current selective pressures. For example, higher fat deposition in little brown myotis or hibernation in colder and drier microclimates could be "survival phenotypes" associated with particular genotypes that are therefore associated with positive population growth (Haase et al. 2021, Frick et al. 2023). Once these traits are identified (Step 2), interventions can be developed and applied to deliberately support selection on these currently favorable traits (Step 3). Finally, monitoring and evaluating outcomes of applied interventions is critical to determine effectiveness, and to identify unexpected impacts that reduce fitness or reduce genetic diversity, negatively impacting resilience in the face of other new threats. An inherent conundrum in this process is that supporting evolutionary rescue in endangered populations will by definition favor some genotypes over others (i.e., survival of the fittest), reducing genetic diversity (and therefore adaptive potential) of the population overall. Wrestling with this conundrum is beyond the scope of this paper, but we acknowledge it here because supporting evolutionary rescue requires us to strike a balance between the goals of Steps 1 and 3.

In the case of WNS, specific heritable traits that confer observed tolerance or resistance to WNS in species and populations (Frick et al. 2017a) remain unclear, so strategies (i.e., Step 3) that support selection for multiple candidate "survival phenotypes" are warranted. For instance, if increased pre-hibernation fat deposition is under selection then we should strive to identify, protect, and enhance fall roosting and foraging habitats (Frick et al. 2023) and monitor how abundant resources influence this survival phenotype and genotype. If particular gene variants associated with hibernation energetics and arousal confer higher survival of WNS, we should aim to understand how those genes affect hibernation phenotypes, how those phenotypes are adapted to different hibernaculum microclimates, and how interventions like microclimate manipulation (e.g., Turner et al. 2022, Boyles et al. 2023) might influence selection on hibernation traits and bat survival. In general, maximizing genetic and phenotypic diversity in bat populations also increases the probability that populations will persist through future, emerging threats.

A precautionary approach to evolutionary rescue necessitates strong conservation measures that maintain and support all populations of susceptible species, not just those for listed species or in regions where disease poses an imminent threat. For hibernating bats that are susceptible to WNS, strategies to support evolutionary rescue include protection of hibernation, roosting, and foraging habitats on both private and public lands, as well as minimizing other causes of mortality where possible. Outreach or incentive programs can encourage landowners to preserve forest habitat, leave abandoned structures in place, maintain bat roosts, limit roost disturbance by humans, or provide artificial roosts in appropriate settings. Removal of invasive species and restoration of degraded ecosystems using native species and nature-based solutions can also improve foraging habitats for bats. These proactive area-based protection measures can support population growth and resilience ahead of a disease epidemic and enable recovery by allowing dispersal of individuals back into habitats from which the species was extirpated. In combination, these evolutionary rescue strategies can help preclude the listing of species and the necessity for more stringent protections to prevent extinction. Research on other stressors that may affect populations that have been reduced by disease is also a top priority to facilitate adaptive management. Such measures will take on increasing importance as populations that survive WNS struggle to repopulate in decades to come, particularly in the face of cumulative threats.

INTEGRATE THE PUBLIC SECTOR AND HUMAN SIDE OF BAT RESEARCH AND CONSERVATION

Influencing beliefs, knowledge, and attitudes of people and decision makers about bats (e.g., Stracka et al. 2020) is fundamental to effective and deliberate bat conservation on public and private lands. As WNS spreads across North America, landowners, the general public, and Indigenous Peoples have been playing key roles in reporting sick bats to states, provinces, and NGO officials, identifying bat colonies on private and crown/public land, and allowing access to those colonies for research or management purposes. These groups are also being engaged in opportunities for monitoring bat populations and allocating support for bat conservation education and research.

Historically, social science research has been conspicuously absent from the global bat literature (Kingston 2016), but human dimensions studies relevant to WNS followed the uptick in ecological research since the discovery of *P. destructans* in North America. These studies highlight the need for continued research to better understand stakeholder behaviors, and what might encourage the public and policy makers to take actions that benefit bats (Fagan et al. 2018, Lu et al. 2020, MacFarlane and Rocha 2020, Siemer et al. 2021). Even in New York State, ground zero for WNS, and a place where communication about WNS has been evident in press releases and newspaper articles since 2007, landowners know relatively little about the disease (Siemer et al. 2021). Vulnerability to a risk (i.e., bats being vulnerable to WNS) can predict actions to mitigate that risk, however, without knowledge of the threats bats face, landowners might be more complacent to take actions. This could be especially true given that perceptions about disease are a lens through which landowners filter messages and many individuals have false ideas about the actual risks of rabies and WNS (Siemer et al. 2021). Messages lacking a pro-conservation element, or that only amplify negative misconceptions about bats could be counterproductive for maintaining people's engagement in activities that support evolutionary rescue (López-Baucells et al. 2023). Some research showed shifting public attitudes toward bats can benefit from fine-tuning messages to match the world view of the audience (Lu et al. 2020). Crafting effective outreach based on social science will be particularly important given how news media can diffuse and amplify (mis)information (Nanni et al. 2022), and the potential for other zoonotic diseases, such as rabies and COVID-19 to taint the way that bats are perceived (MacFarlane and Rocha 2020, Sasse and Gramza 2021, Siemer et al. 2021).

These insights demonstrate the importance of supporting social science approaches to guiding public engagement and policy action (Shapiro et al. 2021), with implications for an evolutionary rescue management and conservation approach. As conservation efforts for bats expand, inclusion and engagement of diverse audiences, from inner-city to rural populations, and from metropolitan to Indigenous governments, will be needed. The challenge will be to effectively reach each audience with messages about the benefits of bats, promote strategies for evolutionary rescue, and harness the power of collective action by building capacity, coordinating efforts, and enabling broader participation in bat conservation. Community science programs organized at the state (e.g., Colorado Bat Watch; https://coloradobatwatch.org/) and province level (e.g., Community Bat Programs in Canada) or focused on specific species (e.g., spotted bats; https://osucascades.edu/HERS/northwest-bat-hub/audible-bat-project) or habitats (e.g., Climbers for Bat Conservation; https://climbersforbats.colostate.edu/) are helping to achieve these goals. Annual WNS Grants to States and Tribes administered by the U. S. Fish and Wildlife Service and regional Native American Workshops on Bats (e.g., https://www.usgs.gov/centers/fort-collins-science-center/news/usgs-researchers-are-organizing-first-pacific-northwest) also support essential capacity and collaboration among diverse partners in bat conservation and WNS response. However, more investments are needed in these areas. Adopting a biocultural framework for bat conservation that integrates different knowledge systems and cultural ways of knowing to inform research questions and methods could also help broaden this engagement and shape pro-conservation messages (Pfeiffer and Voeks 2008, Lindholm and Ekblom 2019).

The challenges of clear communication with the public may be offset by a unique opportunity to capitalize on a 30-year increase in positive perceptions of bats (George et al. 2016), which is reflected in increasing public participation in science efforts (Gristwood 2019, Strasser et al. 2019). Community science initiatives can generate large quantities of data across landscapes with minimal cost and staff time, and provide opportunities for participants not only to interact with wildlife and nature but also learn about and protect bats and their habitats, create or restore habitats, communicate observations and data, and show support for policies or demand government actions. Creating online portals (e.g., https://whitenosesyndrome.org) for people to become educated, make bat-friendly decisions, and report bat observations (e.g., https://vtfishandwildlife.com/learn-more/living-with-wildlife/got-bats; https://batwatch.ca) allow for government agencies and other stakeholders to harness the power of public engagement to support bat conservation. Other community science platforms (e.g., https://iNaturalist.org) can be used to support specific, coordinated projects or mined for data, and bat-specific outreach and education programs (e.g., International Bat Week, BCI 2022) can further build social capacity for bat conservation when championed and funded.

Effective communication is also foundational to building cross-sectoral relationships and identification of evolutionary rescue contributions from beyond the conservation sector. In the case of bats, integrated pest-management plans and policies were developed for bats in buildings and other structures by land management agencies and pest-control companies that incorporated bat-friendly techniques for excluding nuisance bats from structures and shared information about bat presence with the local wildlife agency. Following the emergence of WNS, "Acceptable Management Practices for Bat Control Activities in Structures" was also developed as a guide for nuisance wildlife control operators (White-nose Syndrome Conservation and Recovery Working Group 2015). The National Wildlife Control Operators Association voluntarily developed a fee-based bat training course and certification using these guidelines (NWCOA 2021). More recently, the Departments of Transportation and Association of Fish and Wildlife Agencies in the U.S. adopted a resolution to consider the impacts of transportation infrastructure expansion and maintenance on bats (White-nose Syndrome Conservation and Recovery Working Group 2018, AFWA 2023). The resolution recognizes the importance of state, provincial, Indigenous, and territorial fish and wildlife agencies collaborating with their respective departments of transportation to survey for bats at all bridges and culverts and encourages use of national Bats and Transportation Structures (BATS) survey protocols and submission of data to the North American Bat Monitoring Program (NABat; https://www.nabatmonitoring.org/). The uptake of messaging and practices by pest control operators and infrastructure departments to minimize mortality of bats during exclusion, construction, and maintenance activities required for public health and safety emphasizes the importance of targeted outreach and engagement with novel sectors and the process and benefits of a One Health approach.

In summary, education and outreach to the public and diverse stakeholders, coupled with insights from the conservation social sciences, enhance cross-sectoral responses to WNS and ultimately support evolutionary rescue in two ways: (1) by appropriately framing messages about the value of protecting bat populations while communicating thoughtfully about negative stigmas and legitimate human health concerns and (2) by authentic consultation and co-management of bat populations with diverse agencies, sectors, and communities, which underpins a One Health approach. Despite recent gains in cross-sectoral contributions to WNS response and bat conservation, additional efforts to quantify and communicate the value of bats and impacts of bat declines on social and economic values could help expand partnerships and investments. For example, a recent study by Frank (2024) illuminated cross-sectoral effects linking bat population declines caused by WNS with a 30% increase in pesticide use by farmers and 8% elevated human infant mortality rates within counties coincident with the spread of WNS across the eastern half of the United States. Crop revenues also decreased over this time suggesting that high investments in artificial insecticides could not compensate for the loss of natural insect control services provided by bats. This economic analysis illustrates how drastic loss of bats can have ripple effects on environmental health, economics, and public health, making bat conservation more directly relevant to social sectors.

LEVERAGING GOVERNANCE AND POLICY

Governance and policy can be strengthened to compel long-term actions to support evolutionary rescue, but only if political will supports this approach (i.e., constituents support and advocate for measures to protect wildlife health). The U.S. Endangered Species Act, Canadian Species at Risk Act, associated regulations, and related state, provincial, and territorial legislation and regulations, can provide policy support for evolutionary rescue. By responding early to threats, regulators and land managers can implement actions to increase protections of species' habitats and genetic diversity (WCC 2020), and consider extending additional protections or conservation actions that benefit species. However, processes for these mechanisms are generally slow and laborious; gaps in protection and conservation may persist even after listing if implementation does not match "on paper" protection.

In the U.S., listing a species for federal protection under the Endangered Species Act (ESA) involves a multi-step process including a formal species status assessment, a proposed determination, public comment period, and then a final ruling. The whole process can take years and can be further delayed by backlogs and insufficient capacity and funding in the U.S. Fish and Wildlife Service (USFWS). The intensive and often slow process results in limited ability for federal protection under ESA to be used as a proactive response to emerging infectious disease threats to wildlife (Ruhl 2004, Allen et al. 2011). Despite rapid awareness of the severity of WNS-caused population declines of multiple species (Frick et al. 2010, Langwig et al. 2012), the first listing decision was enacted in 2015 for northern long-eared myotis, eight years after the first observation of the disease. Northern long-eared myotis was initially listed as threatened with a 4d rule (USFWS 2015), which resulted in somewhat limited protections for the species. As a result, several organizations sued the USFWS and were able to remand the 2015 final rule (Center for Biological Diversity v. Everson, 435 F. Supp. 3d 69 (D.D.C. 2020)). A final ruling of endangered for northern long-eared myotis was announced effective January 2023 (USFWS 2022a), nearly 16 years after the first observations of WNS in upstate New York. Similarly, tricolored bats were only proposed as endangered in October 2022 (USFWS 2022b) and an assessment for little brown myotis is underway. Once listed on the ESA, development and adoption of recovery plans and commitment to further actions also can take years.

In Canada, species' conservation status is assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), an independent, scientific advisory group that recommends species to the Minister of the Environment for listing using IUCN Red List criteria under the Species at Risk Act (SARA). The decision by the Minister to list, however, often involves consultation with the public and consideration of socioeconomic factors, and may take years (Turcotte et al. 2021). Once listed, a recovery plan is developed for threatened and endangered species to guide the recovery of the species on federal lands, and identification and protection of its critical habitat. The assessment and listing of little brown myotis, northern long-eared myotis, and tricolored bats presented an unusual circumstance, in that the assessment was conducted as an emergency (COSEWIC 2013), and the subsequent listing on Schedule 1 of SARA proceeded relatively quickly. This in turn triggered the development of a multi-species recovery plan, including identification of some categories of critical habitat, but mapping and protection of hibernacula only (ECCC 2018), which have not been updated since then, in spite of much new knowledge. In Canada, although migratory birds and aquatic species at risk are legally protected anywhere they occur in the country, for all other terrestrial species, SARA directly applies only to federal lands (Auditor General of Canada 2023). There are, however, discretionary powers (emergency order, safety net; Auditor General of Canada 2023) that can be applied to private or provincial lands (the majority of Canada's landbase) though these powers have only been used three times and all in response to stakeholder threats of litigation (Auditor General of Canada 2023). Thus, the conservation of most terrestrial vertebrates, including bats, falls to the provinces and territories, and yet only half of these jurisdictions have their own species at risk legislation, with varying degrees of strength (Ray et al. 2021).

Despite differences in the policy process used to list species in the U.S. and Canada (Waples et al. 2013), the conservation implications are very similar. In theory, legal protection of the three bat species will compel the effective protection of populations and their habitats, but protection on paper for the species and their habitats only exists in practice when existing legislation and policies are implemented and, when necessary, enforced.

Additionally, effective protection of important habitat for volant, often far-ranging animals, is best achieved via collaborations across jurisdictions and stakeholders, using standardized and accessible monitoring methods. In 2015, Canada, U.S., and Mexico issued a "Letter of Intent" (Government of Canada 2015) outlining how they will, "work together to monitor bat populations and address the threats that affect them." Since then, the formation of the North American Bat Conservation Alliance (https://batconservationalliance.org) has provided a framework for this collaboration with the first State of the Bats Report released in conjunction with Bat Conservation International in 2023 (https://digital.batcon.org/state-of-the-bats-report/2023-report/). Additionally, NABat is a cross-border initiative, with an established monitoring grid network across U.S. and Canada, standardized methodologies (Loeb et al. 2015, Reichert et al. 2018), and a centralized repository for data from U.S. and Canada. With data from NABat, continental scale analyses of species status and trends have already begun (e.g., Udell et al. 2022).

Unfortunately, policy options for bats are largely limited to listed threatened and endangered species in the U.S. and Canada. This means that most will not get attention until they reach a crisis point, often after populations have declined and lost much of their standing genetic diversity that might help support evolutionary rescue. However, risk assessments can be done pro-actively; for species lacking WNS mortality data, ecological and energetic traits can inform risk assessments (Langwig et al. 2012, 2016, Frank et al. 2019, Bernard et al. 2020, Davy et al. 2020, Haase et al. 2021, Hoyt et al. 2021, McGuire et al. 2021, Grimaudo et al. 2022, Gmutza et al. 2024). In this context, increased attention to the One Health framework, especially after the COVID-19 pandemic, provides new opportunities to empower resource managers to use One Health perspectives to identify, minimize, or avoid impacts on species that are likely susceptible to an emerging disease threat.

Wildlife health management for resilient species and recovery of threatened populations requires sufficient funding, often from varied government and philanthropic sources, and research support for managers. In the U.S., some state natural resource agencies preemptively elevated the threat assessment ranking of species soon after the emergence of WNS. In the U.S., states can include species of concern in State Wildlife Action Plans, which then include species on the national list of Species of Greatest Conservation Need (https://www1.usgs.gov/csas/swap/), and can lead to threat-focused research or monitoring funding opportunities, such as State Wildlife Grants (https://www.fws.gov/program/state-wildlife-grants). In Canada, listing of the three bat species brought about increased attention, including their prioritization for habitat stewardship funding (https://www.canada.ca/en/environment-climate-change/services/environmental-funding/programs/habitat-stewardship-species-at-risk.html).

Achieving evolutionary rescue takes time and requires consistent, long-term protection of individuals and their habitats. The timeline for evolutionary rescue will depend on the population, the threat, and their potential co-evolution. Government funding (i.e., the proposed Recovering America's Wildlife Act in the U.S.) to support surveillance or conservation actions like State Wildlife Action Plans can support robust means to measure whether populations have stabilized or are recovering. Action plans could also track the efficacy of certain conservation actions that may only be deployable at local scales or over short grant-cycle time frames. Protection and conservation of threatened species need to be well orchestrated, implemented, and enforced to achieve reduction of harm to the species and its habitats, with research providing the evidence base for decision makers.

Policies that encourage early cross-sectoral collaborations and trans-disciplinary learning can introduce cost efficiencies to leverage analytical expertise and observations of species persistence. They can also contribute to 360° assessments of stressors influencing the health of threatened and declining species, informing mitigation measures, and establishing standardized diagnostic criteria to support stakeholders and communication about diagnostic pathogen detection and disease emergence in new areas. To contribute directly to bat conservation, these efforts must culminate in effective science communication to policy makers who can directly impact species recovery and resilience (Table 1). In sum, the governance and policy sector can build on public sector support to (1) use and expand policies to protect at-risk species; (2) enhance One Health actions to protect threatened species; (3) implement policies by federal, state, provincial, Indigenous, county, town, and municipal level governments to achieve protection; and (4) create reliable funding mechanisms and tap cross-sectoral support to grow conservation and research efforts for at-risk species.

SUPPORT EVOLUTIONARY RESCUE WITH SCIENTIFIC INVESTIGATIONS AND DATA COLLECTION FROM THE RESEARCH SECTOR

Effective management of threatened species relies on comprehensive data about target species needs (Hochkirch et al. 2021, Gorman et al. 2022). Given substantial knowledge gaps remain for most North American bats, including roost-site selection, minimum viable home-range sizes, and winter ecology (Bernard et al. 2020, Davy and Willis 2023), management decisions are often made in a vacuum. Research will improve understanding and management of these important natural history aspects for evolutionary rescue. Detecting signals of evolutionary rescue relies on a comprehensive understanding of baseline traits and how these and other traits shift after a selective sweep such as the arrival of WNS. Science on how to detect the earliest signals of evolutionary recovery is needed. Long-term monitoring and research to detect population and genetic changes will be important. Most competitive grants last only a few years, therefore there should be some rethinking of how research is done and funding frameworks are structured to support long-term research efforts that help guide management approaches. For example, evolutionary rescue and wildlife health surveillance research could be integrated into or modeled after the National Science Foundation's Long Term Ecological Research Network (Hobbie et al. 2003). This program is designed for interdisciplinary research on how ecological systems function and change over time, a model that could be adapted to better understand processes behind evolutionary rescue (e.g., baseline data for trend identification, cross-site comparisons on how evolutionary rescue is influenced by different contexts or factors) with a focus on problem-oriented applied research and stakeholder engagement.

Systematic, range-wide efforts like NABat can provide important information for coordination of local, federal, state, and provincial agencies, non-governmental organizations, and universities in a multi-agency program. NABat collects and analyzes bat occurrence and relative abundance data, to improve baseline and trend estimates of each species' occurrence and abundance across North America (Reichert et al. 2021, Udell et al. 2022). Encouraging members of the public to submit data (e.g., photos or observations) to state and provincial governments who regularly submit data can further public engagement and NABat's goals to inform bat conservation decisions. In western Canada, Wildlife Conservation Society Canada's BatCaver program (https://www.BatCaver.org) works with cavers across British Columbia and Alberta to deploy bat detectors and temperature and humidity loggers underground in hundreds of locations for winter monitoring, locating cave hibernacula, and describing hibernaculum microclimates. A similar caver-biologist coordination program in Montana resulted in the discovery of new bat overwintering sites (Bachen et al. 2020). Occurrence data and ecological knowledge allow scientists to quantify the factors that influence winter bat distributions (McClure et al. 2021), where bats persist, and where to target interventions.

Investments in collaborative surveillance to detect pathogen arrival and emergence of disease are key components of tracking disease and managing for evolutionary rescue. As WNS continues to invade western North America and into Mexico, continued surveillance and sharing and dissemination of information (e.g., resources and status maps on https://www.whitenosesyndrome.org) is critical for understanding the pathogen's ecology and its ecological impact. In cases where a pathogen's effects cannot be mitigated, early detection of emerging pathogens allows policy makers and managers to increase surveillance, and plan potential interventions designed to reduce mortalities during the epizootic phase and facilitate evolutionary rescue (e.g., targeted habitat protection or treatments to reduce infections or disease severity). For wildlife diseases in general, collaboration, coordination, and harmonization of diagnostic approaches at an early stage is essential, and should engage all stakeholders in communication of results.

Throughout North America, bats hibernate in a wide variety of locations. Understanding where bats overwinter is a critical component of being able to assess risk and make management decisions, as it pertains to habitat protection, WNS surveillance, and potential interventions. Many bat species across western North America appear to use diverse hibernacula. These include caves and mines, human-made structures (buildings, bridges, tunnels, and culverts), exposed rock outcrops, talus slopes, or root-wads (Lausen and Barclay 2006, Burles 2014, Klug-Baerwald et al. 2017, ECCC 2018, Blejwas et al. 2021). Little is known about where bats hibernate in western and northern reaches of the continent (Wilson 2014, Weller et al. 2018, Slough et al. 2022). In the western U.S. the only published assessment of occupancy and bat population trends during winter is limited to analyses of Townsend's big-eared bat

(*Corynorhinus townsendii*) and *Myotis* spp. at the genus level (Weller et al. 2018). This uncertainty surrounding where bats hibernate across western North America, precludes winter observations in many locations. This is reflected in the significant research gaps about the winter ecology for many western species, and western populations of some continent-wide species. For example, of what is currently known about the hibernation ecology of little brown myotis, western populations seem to differ from eastern populations (Blejwas et al. 2023) but where this species hibernates across its western range is poorly known (Wilson 2014, Weller et al. 2018, Slough et al. 2022). Flight activity of some western bats during winter has elucidated general locations where bats are overwintering (e.g., Lausen and Barclay 2006, Lausen et al. 2022a) but exact hibernacula features remain largely undiscovered, and the ecological underpinning of why bats fly outside their hibernacula remains largely unknown (Lausen et al. 2022a). In areas where hibernacula are unknown or inaccessible, maternity colonies of species that aggregate in man-made structures or trees have become a focus for population monitoring, disease surveillance, and management interventions.

Other knowledge gaps that also limit conservation planning and action include which species co-roost together, winter activity patterns (e.g., Klüg-Baerwald et al. 2016), and intra-annual movements (Norquay et al. 2013). As tracking devices become smaller and genetic techniques improve, they can help us understand bat movement and winter dispersal and answer questions like, how do we maintain connectivity among drastically reduced populations and how much gene flow is needed to provide the genetic variation and dispersal required for successful evolutionary rescue (Castle et al. 2015, Weller et al. 2016, Taylor et al. 2017).

Trans-disciplinary research that can help managers take decisions and actions on threats and stressors (Jones et al. 2009, Voigt and Kingston 2016) presenting population pressures alongside a disease risk is paramount. Co-infections with native North American bat coronaviruses can increase the severity of WNS (Davy et al. 2018). Bat populations also face many additional threats (Frick et al. 2020), including mortality due to wind energy development (Arnett et al. 2016, Frick et al. 2017b, Davy et al. 2021), vehicle collisions and habitat degradation associated with roads (e.g., Kitzes and Merenlender 2014), habitat destruction and fragmentation from timber harvest (e.g., Yates and Muzika 2006), and mortality associated with ill-designed artificial roosts in a changing climate (Bideguren et al. 2019, Lausen et al. 2022b). The scale and severity of many of these impacts are unknown, particularly where and when they interact synergistically. To complicate matters, the most immediate and detrimental impacts of climate change may include increased drought (Cappelli et al. 2021) and reduced water availability (Adams 2010). Climate change could also help abate the energetic stress of WNS through shorter, milder winters (McClure et al. 2022). Complex climate change influences are compounded with unknown impacts of ongoing forest and wetland loss on high-quality roosting and foraging habitat (EPA 2016, Jung and Threlfall 2016, Korine et al. 2016, Fuller et al. 2020). An open question is whether habitat loss and pollution from pesticides and fertilizers, together with wide-scale use of biocides, compromise bat prey biomass and consequently the ability to build fat stores critical for overwinter survival (Jones et al. 2009, Hallman et al. 2017, Lister and Garcia 2018, Allgeier et al. 2019, Cheng et al. 2019, Forister et al. 2019, Sánchez-Bayo and Wyckhuys 2019). Declining body size at little brown myotis maternity colonies in Yukon, Canada over a 15-year study suggested chronic nutritional stress associated with increased rainfall, and potentially with reduced insect abundance (Davy et al. 2022). More fundamentally, researchers have yet to rigorously tackle the potential threat of pesticides, not only on bat prey species and overall bat recruitment, but also bat health (Frick et al. 2007, Oliveira et al. 2021, Sandoval-Herrera et al. 2021). This research is urgently needed as an overwhelming lack of knowledge about adjacent threats and impacts limits the scope of actions managers can take and is itself a threat (Frick et al. 2020).

INVEST IN ONE HEALTH APPROACHES TO SUPPORT EVOLUTIONARY RESCUE

A One Health approach embraces diverse multidisciplinary research teams and cross-sectoral engagement to implement evidence-based conservation actions (Gruetzmacher et al. 2021, OHHLEP et al. 2022). The approach is already championed as a way to address emerging health threats around the world precisely because the threats themselves, like evolutionary rescue, are a result of social-ecological dynamics playing out on diverse landscapes and require going beyond traditional academic boundaries. The global prevention strategy for highly pathogenic avian influenza (HPAI) emphasizes a One Health approach, including social science, policy, and engagement with representatives from human, animal, and environmental sectors (FAO and WOAH 2025). HPAI is an ongoing threat that requires the breadth of scientific methodologies from virology to ethnography to political governance studies in addition to stakeholder engagement and enabling policies to fully characterize and manage the risk to animals, humans, and economies. In the Republic of Congo, conservation teams deliver targeted outreach to communities at risk on Ebola prevention measures while engaging the help of those communities in detecting wildlife mortality events (Kuisma et al. 2019). Here conservation actors are able to access rural communities that local public health officials do not have staffing or resources to reach. In Cambodia, the government livestock agency and conservation stakeholders team to monitor endangered gaur (*Bos gaurus*) and banteng (*B. javanicus*) and in response to a detection of Lumpy skin disease jointly delivered a campaign to ring vaccinate cattle in the surrounding communities (Porco et al. 2023). With cross-sectoral threats like HPAI and Lumpy skin disease, collaboration can open up win-win solutions that benefit all, including human and livestock health.

Prevention of disease should be recognized as the most effective and affordable strategy for complex conservation issues associated with wildlife health. Responding to wildlife diseases as they emerge is costly and often ineffective at limiting spread and impacts due to gaps in knowledge, lack of scalable solutions for population-level benefits, limited resources, and the need to balance competing management objectives (Langwig et al. 2015, Bernard et al. 2019, Russell et al. 2020, Hohoff et al. 2024). In periods of no imminent threat, One Health approaches are good practice for baseline conservation. Once a disease is introduced and becomes established in a wildlife population, or endemic, it is nearly impossible to eradicate and efforts to mitigate impacts can demand a mix of short- and long-term investments and complex decisions in the face of uncertainty.

For emerging health threats structured decision making can help governing bodies and managers charged with protecting wildlife make very difficult decisions to optimize management objectives and balance disease risks and uncertainty. It has already been used by managers to navigate the entire WNS problem space, from investments in research, interventions, or more traditional conservation management actions like habitat or roost protection (Bernard and Grant 2019, Bernard et al. 2019, 2020). The process can help managers weigh decisions about short-term, often tech-based interventions that may help buy time against long-term management goals and scenarios where disease eradication may not be feasible.

Populations threatened by diseases often face other significant threats that stretch their adaptive capacity and amplify extinction risk (Davy et al. 2017b, Seltmann et al. 2017). Cumulative stressors, including continuing habitat loss and degradation, reduced access to insect prey and water sources, and additive mortality (O'Shea et al. 2016, Voigt and Kingston 2016, Frick et al. 2020) can limit adaptive capacity, and must be minimized to support evolutionary rescue. Even when threats are mitigated, small populations are more vulnerable to demographic and environmental stochasticity (e.g., the extinction vortex), and evolutionary rescue has an uncertain timeline. Therefore, recovery of bats impacted by WNS, or other taxa impacted by emerging infectious diseases, requires trans-disciplinary and trans-sectoral approaches, and long-term commitments to habitat protection and reduction of avoidable mortality (Table 1).

In this synthesis we described how to facilitate evolutionary rescue from an emerging disease through public engagement, policies and governance, and continuing to learn more about the ecology of bats and pathogen spread. We emphasized the importance of framing messages for the public appropriately, integrating more diverse audiences, and using communication and outreach to promote actions that are good for wildlife and good for people, with care taken to avoid creating negative attitudes toward wildlife. Pertaining to the governance sector, we highlighted the importance of building policy mechanisms like dedicated species at risk legislation, if it does not already exist, and practicing earlier implementation of both traditional and more integrative policies, capitalizing on public support to generate reliable resources to enhance the conservation of threatened species. Conservation and prevention success also relies on enforcement of regulations. For example, rinderpest, a deadly cattle virus, was successfully eradicated with international biosecurity policies and coordinated livestock vaccinations; whereas illegal movement of pigs and pork products has contributed to the spread of African swine fever, which is threatening endangered pig species (Luskin et al. 2021). The learning aspects of continued surveillance and research will need greater policy and public sector support. Successful cross-sectoral and multi-disciplinary platforms like NABat show the potential of large long-term collaborative and scalable science that drives insights on species presence, stressors, and health.

When evolutionary rescue is the only promising sustainable solution among options available, managers will need research support and new tools to navigate the social-ecological uncertainties. Interventions that provide a short-term benefit and maintain genetic diversity can buy time for continued study and development of tools, but then they must be evaluated in the context of potential long-term consequences on natural selection. At a minimum, there needs to be awareness of an intervention's potential benefits, risks, efficacy, long-term costs, and objectives (e.g., as a stop gap measure until a better solution is discovered). Risks include potentially altering (positively or negatively) the natural trajectory of evolutionary rescue. The precautionary principle fully aligns with cross-sectoral actions supporting evolutionary rescue to do more to support populations of bats. We stress the importance of a One Health approach, essentially a commitment to the long-term cross-sectoral support of species resilience.

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