Disease-smart climate adaptation for wildlife management and conservation

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Climate change is a well-documented driver and threat multiplier of infectious disease in wildlife populations. However, wildlife disease management and climate-change adaptation have largely operated in isolation. To improve conservation outcomes, we consider the role of climate adaptation in initiating or exacerbating the transmission and spread of wildlife disease and the deleterious effects thereof, as illustrated through several case studies. We offer insights into best practices for disease-smart adaptation, including a checklist of key factors for assessing disease risks early in the climate adaptation process. By assessing risk, incorporating uncertainty, planning for change, and monitoring outcomes, natural resource managers and conservation practitioners can better prepare for and respond to wildlife disease threats in a changing climate.

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Maintaining healthy wildlife populations is a central mission of natural resource management agencies. Although what constitutes a "healthy" wildlife population is often debated, health reflects the natural capacity of a population to cope with environmental change or stochastic events, and integrates biophysical processes with societal needs and knowledge (Stephen 2014). Infectious disease is a specific component of health that conservation practitioners are tasked with monitoring, minimizing, and preventing in wildlife populations, with implications for long-term conservation (Hanisch *et al.* 2012). As a threat multiplier and well-documented driver of infectious disease, climate change further complicates this task (Hofmeister *et al.* 2010). However, wildlife disease management and climate-change adaptation have largely operated in isolation, which impedes conservation progress. Effective wildlife management requires practical approaches for preemptively addressing both stressors in research, planning, and decision making.

In a nutshell:

- Although interconnected, wildlife disease management and climate-change adaptation have followed separate pathways and have yet to be formally integrated in practice
- We offer four case studies to demonstrate how climate adaptation can have unintended consequences—including negative or maladaptive outcomes—for wildlife disease risks
- We provide general guidance for disease-smart climate adaptation, advancing the role of conservation practitioners in reducing the risk of adverse disease outcomes

Climate adaptation is an applied discipline that aims to reduce harm to natural systems caused by climate change or, alternatively, to exploit beneficial opportunities. Although climate adaptation strategies have been standardized to an extent, many adaptation actions (ie climate-informed approaches to wildlife management) are novel and can have unpredictable effects on infectious disease. Unless disease or other wildlife health-related threats are a primary concern for the target species or system, most disease considerations in the climate adaptation process are afterthoughts resulting from unintended consequences. A recent review found that only 1% of climate adaptation recommendations addressed infectious disease, highlighting an urgent need for greater incorporation of proactive disease management in such efforts (LeDee *et al.* 2021). To date, practitioners lack guidance on how to manage wildlife disease alongside climate adaptation.

We present a set of case studies to illustrate how climate adaptation can have unintended consequences for wildlife disease dynamics. Because climate adaptation efforts are increasing in number and scale, we offer guidance on how to improve outcomes by proactively taking a disease-smart

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Figure 1. A disease-smart approach to climate adaptation (aspects of which are highlighted in orange) integrates an additional layer of disease-risk assessment early in the planning process and explicitly includes disease considerations when setting and evaluating adaptation goals. Furthermore, identifying and implementing disease-smart adaptation actions and early monitoring for key disease indicators will help to both reduce climate-change vulnerability and promote wildlife health.

approach to adaptation (Figure 1). Through incorporation of best practices for disease-smart adaptation and identification of key factors for assessing disease risks throughout the climate adaptation process, we offer natural resource management agencies, Indigenous nations, and nongovernmental organizations an approach to prepare for, and respond to, wildlife disease threats when planning climate adaptation actions.

Potential unintended consequences for wildlife disease

Climate adaptation is a rapidly expanding discipline; however, most recommendations for climate adaptation are reflected in the seven general adaptation strategies that compose the National Wildlife Federation's Climate-Smart Conservation guidelines (Stein *et al.* 2014). For each of these adaptation

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strategies, we discuss the intersection with wildlife disease and potential unintended consequences for wildlife populations.

Ensure connectivity

Defined as the degree to which landscape structure facilitates an organism's movement, landscape connectivity is a frequently recommended climate adaptation strategy. Maintaining connectivity has numerous benefits for species when responding to climate change (eg supporting range expansion, facilitating gene flow). Actions to increase connectivity may include creating corridors, removing barriers, and establishing buffer zones. However, greater connectivity may exacerbate disease transmission by increasing host density, facilitating pathogen movement, and improving pathogen persistence via metapopulation dynamics (Hess 1994). In some systems, benefits to the host from increased connectivity can outweigh the risks of pathogen transmission; however, in systems where increased connectivity is a good predictor of disease spread, the negative consequences of host dispersal should be explored to meaningfully address trade-offs. For example, both field research and population modeling indicate that, in North America, prairie dog (*Cynomys* spp) movement among colonies maintains genetic diversity within metapopulations but also facilitates outbreaks of *Yersinia pestis*, the flea-borne bacterium that causes sylvatic plague (Shoemaker *et al*. 2014; Russell *et al*. 2021). Mortality from plague can be near 100% in prairie dog colonies (Collinge *et al*. 2005; Russell *et al*. 2021). These outbreaks have important consequences for the critically endangered black-footed ferret (*Mustela nigripes*; Figure 2a) because ferrets are highly susceptible to plague and rely on prairie dogs as a primary food source and habitat architect (Collinge *et al*. 2005). Natural barriers to connectivity help reduce disease spread among prairie dog colonies (Collinge *et al*. 2005), raising the possibility of using strategically placed barriers to manage plague outbreaks and spillover in high-risk landscapes. When disease transmission risk is addressed early in the adaptation process, vulnerable species can be protected through either the co-implementation of selective pathogen mitigation efforts, thereby increasing the substructure of connected populations (ie populations with varying levels of connectivity; Russell *et al*. 2020), or

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Figure 2. (a) Black-footed ferret (*Mustela nigripes*) (image credit: T Rocke). (b) Desert tortoise (*Gopherus agassizii*) (image credit: Joshua Tree National Park). (c) ʻIʻiwi or scarlet honeycreeper (*Drepanis coccinea*) (image credit: USFWS Pacific Region). (d) PacifiCorp's Copco 1 Dam on the lower Klamath River, in northern California (image credit: River Design Group).

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the creation of strategic landscape barriers to disrupt host or vector dispersal (Shoemaker *et al.* 2014).

Protect refugia

Protection of climate-change refugia can facilitate species survival by ensuring access to locations with unique biotic or abiotic characteristics that may provide buffering from adverse conditions (Morelli *et al.* 2020). Refugia not only offer biophysical conditions suitable for persistence but also enable species to survive stochastic disturbances and recolonize suitable habitat after disturbance events (eg disease outbreaks; Russell *et al.* 2020). However, climate refugia may result in novel ecological assemblages either intentionally by design or unintentionally as species undergo varying degrees of range expansions, contractions, or shifts (Morelli *et al.* 2020). Intermixing of species that were previously separated by time (seasonally or interannually) or space may facilitate pathogen spread or parasite host-switching (Carlson *et al.* 2022). This phenomenon could be further exacerbated when refugia are defined along contracting ecological gradients that allow pathogens, parasites, and vectors to follow existing hosts or switch to new ones in areas that were previously disease-free (Gupta *et al.* 2019).

Translocate organisms

Translocation of individuals or populations involves human-facilitated movement of organisms from one location to another (and is also referred to as assisted migration or managed relocation). Translocation is intended to facilitate climate tracking within or beyond a species historical range. The reshuffling of species on the landscape is controversial for many reasons, including unintended disease introductions and alteration of wildlife disease dynamics (Kock *et al.* 2010). Pathogen spillover can occur via cross-species transmission or from environmental reservoirs (Russell *et al.* 2020), particularly when animals are stressed or exhibiting behavioral changes due to the move (Aiello *et al.* 2014). Individuals of many candidate species for translocation are subjected to a thorough health evaluation prior to movement and, in some cases, a period of quarantine prior to release. These mitigation strategies give practitioners the opportunity to anticipate and avoid many negative outcomes. However, even these measures may be insufficient to avert all disease outbreaks. For example, despite in-depth guidance and health screenings prior to a translocation of desert tortoises (*Gopherus agassizii*) in the Mojave Desert (Figure 2b; Rideout 2015), an outbreak of an upper respiratory tract disease caused by *Mycoplasma* occurred (Aiello *et al.* 2014). Unusual movement patterns by translocated tortoises likely facilitated rates of contact and transmission that were higher than typical for the species (Aiello *et al.* 2014). Moving animals to new landscapes can impact their behavior and physiology in unforeseen ways, making them more likely to spread pathogens or more susceptible to disease. As climate change continues, practitioners may increasingly be faced with weighing difficult trade-offs between the risks of translocating species versus the risks of allowing them to remain in degraded landscapes. As the example of the desert tortoise demonstrates, not all risks can be fully anticipated prior to action; however, being aware of how disease may adversely impact translocation outcomes is critical for practitioners who hope to help species thrive in new habitats.

Support evolutionary potential

Evolutionary potential is generally bolstered by higher genetic diversity and larger population size (Thompson *et al.* 2023). When these properties are reduced, populations are often more vulnerable to inbreeding depression and accumulation of detrimental alleles (Wilder *et al.* 2020). Similarly, outbreeding depression, or the suppression of local genetic adaptations, can reduce evolutionary potential (Wilder *et al.* 2020) and, in some cases, can increase susceptibility to infectious disease (Goldberg *et al.* 2005). Evolutionary potential can be enhanced through either direct interventions (including genetic rescue, captive breeding and release) or more novel approaches (like genetic engineering and hybridization). These interventions are often considered to be a last resort when a species faces extinction, because they are resource intensive and carry a high risk of unintended consequences. For example, the unprecedented extinction rate of Hawaii's endemic birds (Figure 2c) is primarily due to avian malaria, which is caused by protozoan parasites transmitted by an introduced vector, the southern house mosquito *Culex quinquefasciatus* (LaPointe *et al.* 2012). Climate-change forecasts indicate range expansion of mosquitoes into higher elevations (Liao *et al.* 2015), which are historically considered as disease-free refugia for Hawaii's native birds and therefore may constrain their adaptive capacity. Traditional approaches to controlling avian malaria, such as the use of chemical and biological control agents, often have unacceptable impacts on non-target species. Therefore, researchers are evaluating the use of gene editing for promoting malaria resistance in Hawaiian honeycreepers (Samuel *et al.* 2020) as a more transformative solution to improving species evolutionary potential. However, gene editing (and more broadly, genetic engineering for conservation) remains controversial, and the ethical implications of this approach should be scrutinized alongside the eco-evolutionary and logistical considerations, which will require extensive cross-disciplinary investigation. Genetic management plans should also consider the potential impacts of, for example, captive breeding on host–pathogen dynamics through reduced heterogeneity in genetic loci associated with immune function, disruption of acquired resistance to pathogens, and the general deleterious effects of reduced fitness from incompatible genotypes (Goldberg *et al.* 2005). In situations where species face dire conservation outcomes because of a lack of genetic diversity, direct interventions to bolster evolutionary potential may still

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represent the most promising strategy, regardless of associated disease risks. By fully understanding how these actions impact host immunity, trade-offs can be accurately identified and evaluated.

Restore structure and function

Retaining ecosystem structure (eg habitat complexity) and function (eg nutrient cycling) involves efforts to rebuild, modify, or transform ecosystem components and processes that have been lost or compromised. With respect to climate adaptation, this approach has had a persistence-oriented or "enhancing resilience" focus that assumes fully functioning systems will more likely recover to their prior state after perturbations (Stein *et al.* 2013). More recently, conservation practitioners have begun shifting management beyond resisting changes and retaining existing (or baseline) ecological conditions to also facilitating what many now see as inevitable ecosystem transformations (eg forests to savannas). The resist–accept–direct (RAD) framework is a decision-support tool for identifying management approaches that resist changes to ecosystems, accept changes when they may be tolerable or even desirable, or direct changes to something different than the past to maintain ecosystem structure, function, or services (Lynch *et al.* 2021; Schuurman *et al.* 2022). Although directing ecosystems may become increasingly necessary in transforming environments, unanticipated epizootics may emerge as a consequence of a practitioner's actions. Understanding how changes to ecosystem structure via adaptation actions may affect ecosystem functions, regulations, and interactions (including disease dynamics), along with the triggers and thresholds of ecosystem transformation, may be key to avoiding unintended disease spread.

Protect key ecosystem features

Protection of key ecosystem features often requires a landscape-based approach to management of structural habitat characteristics (eg forest seral stages), critical habitats (eg fish spawning sites), and species that play important functional roles. Adaptation actions in this category may include restoring habitat, implementing disturbance regimes, maintaining hydrological flows, or ensuring the presence of ecosystem engineers. However, although offering promising avenues for increasing climate resilience, these actions may also have unanticipated impacts on infectious disease. In the western US, dam removal has been proposed as a means of recovering freshwater and diadromous fish populations through restoration of migratory corridors and spawning habitat. Four dam removals are planned along the mainstem of the Klamath River near the Oregon–California border (Figure 2d), where Pacific salmon populations are increasingly threatened by the myxosporean parasite *Ceratonova shasta*, whose spread has accelerated under climate warming and drought conditions (Ray *et al.* 2015). Below the dams, *C shasta* has been implicated in substantial mortality of Chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*Oncorhynchus kisutch*). Parasite densities are generally lower above dams, where colder waters and variable flows naturally constrain parasite production (Hurst *et al.* 2012). Proactively considering how pathogen dynamics may change after dam removal, through establishing baseline information on pathogen dynamics above and below dams and monitoring high-risk locations pre- and post-removal, will help to preempt and mitigate unintended disease outbreaks that may threaten restoration success. When climate adaptation strategies focus on landscape features, the impact on infectious disease pathways should be considered to reduce the risk of pathogen introduction or spread.

Reduce secondary stressors

Secondary stressors that are not specifically linked to climate change or that are indirectly linked via impacts to resource availability or altered species interactions are commonly proposed targets for climate adaptation. Targeting secondary stressors (eg invasive species, habitat degradation) can positively influence infectious disease outcomes by alleviating physiological, environmental, or competitive burdens that can exacerbate infectious disease. Conversely, these actions could also unintentionally compound the risks of wildlife disease spread. For example, although resource provisioning is a tractable solution to help vulnerable wildlife populations meet their nutritional needs, it can also increase pathogen transmission through several mechanisms, such as increasing contact rates among hosts at concentrated feeding sites (Civitello *et al.* 2018). Nevertheless, by pairing stressor mitigation efforts with proactive risk assessments, ongoing monitoring, and biosecurity protocols, disease outbreaks can be minimized or avoided.

Best practices for climate adaptation

For conservation practitioners, an overarching goal of climate adaptation is to reduce the risks that climate change poses to natural resources. By taking a disease-smart approach to climate adaptation, practitioners can identify win–win interventions that achieve the co-benefits of reducing disease risk while enhancing species adaptive capacity in a changing climate (Figure 1). Due to the complexity and unique characteristics of ecosystems, we cannot offer a global solution to address disease in wildlife management and climate adaptation. However, Hopkins *et al.* (2022) recommended several management actions for achieving the dual goal of advancing conservation and limiting infectious disease. We also identify key questions that practitioners can ask (Table 1) to assess disease risk factors (Figure 3) when preparing climate adaptation plans and suggest the following best practices for integrating disease

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Table 1. Example adaptation strategies (from Handler *et al.* 2022) that relate to the epidemiological triad (environment, host, and agent) and associated questions to ask during the initial planning phase of a climate adaptation project that link to the checklist of disease risk factors (presented in Figure 3).

Example adaptation strategies	Questions
Environment (landscape)	
• Manage and create suitable microhabitats/microclimates • Create or maintain sources of food, water, and cover in a variety of locations • Maintain or mimic natural disturbance regimes to enhance habitat quality • Create large, intact, or aggregated protected areas • Protect stepping-stones, adjacent reserves, and corridors • Protect climate refugia • Establish corridors and reduce barriers to wildlife movement	Are there existing transmission pathways for known pathogens or disease vectors on the landscape and will adaptation action(s) create, maintain, or obstruct transmission pathways?
	Are there existing hotspots for contact between hosts and pathogens (ie contact zones) and will adaptation action(s) create, maintain, or obstruct contact zones?
	Will adaptation action(s) result in the concentration of animals on the landscape (eg via corridors, supplemental feeding areas, artificial water sources)? If so, is this expected to alter infectious diseases of concern?
	Are the sources of existing pathogens known, including animal or environmental reservoirs? Will adaptation action(s) cause disturbances to the environment or ecological community that may result in disease outbreaks or spread (eg through altered behavior or habitat use)?
	Will adaptation action(s) create environmental reservoirs or habitat for reservoir hosts (eg via wetland restoration)?
Host (focal species) and Agent (pathogen)	
• Maintain and enhance genetic admixture (interbreeding) zones to facilitate adaptive genetic exchange • Maintain populations in disturbed environments because they may contain adaptive traits • Translocate individuals or populations to habitat within the existing range that was formerly occupied and remains suitable (reintroduction) • Conserve leading-edge populations (high altitude, northern, etc) • Manage extant and emerging diseases • Use captive breeding programs to increase populations of declining or rare species	Will adaptation action(s) contribute to physiological stress, mortality, or declines in fitness and thereby susceptibility to disease?
	Has the host species experienced a population bottleneck, substantial population decline, or lower genetic diversity? If yes, was disease a primary cause?
	If disease was previously managed, were past control efforts successful?
	Does the host species have any acquired immunity or innate resistance to endemic pathogens?
	Are adaptation action(s) intended to directly ameliorate disease? If not, are there secondary benefits to disease mitigation or prevention from the proposed adaptation action(s)?
	Will adaptation action(s) increase disease prevalence on the landscape through, for example, disturbance?
	Are there existing disease refugia on the landscape? If so, are they refugia because of an absence of pathogens or vectors, or because of misalignment between host occurrence and infection (or transmissibility) windows?
	If considering translocation, are there known disease vectors or pathogens in the recipient community? If yes, what is their prevalence?
	Will adaptation action(s) result in novel species interactions that could lead to pathogen spillover?
	Are the infection and transmissibility windows for the pathogen known? Will adaptation action(s) result in new or prolonged transmission windows?

Notes: Strategies pertaining to the host and agent are grouped together because the host and agent are inextricably linked and may experience reciprocal effects from adaptation actions.

considerations throughout the climate adaptation planning and action cycle.

Anticipate emerging disease threats

Climate change is expected to impact disease dynamics in many ways, some of which could be difficult to anticipate (Cohen *et al.* 2020). One way to reduce risk (and vulnerability) is to consider wildlife disease early in the climate adaptation process by taking an anticipatory, rather than a reactive, approach. For example, in Australia, the critically endangered northern hairy-nosed wombat (*Lasiorhinus krefftii*) has been historically isolated from disease exposure (Martin and Carver 2021). Despite the current absence of active disease in the population, other closely related wombat species have experienced severe population declines from sarcoptic mange and introduced pathogens (eg the protozoan *Toxoplasma gondii*). Consequently, the species recovery plan for the northern hairy-nosed wombat has taken a proactive approach to pathogen prevention through routine baseline health monitoring, establishment of strict handling hygiene protocols, aggressive control of feral cats, and the development of contingency plans for potential outbreaks. In addition, wombats selected for translocation to mitigate against climate-change threats undergo thorough health and mite screenings (per recommendations in Horsup [2004])—efforts that have helped to avoid further population losses.

Recognizing that disease is an integral component to ecosystems, with its own ecosystem-like components and processes, will strengthen our understanding of the totality of disease implications for ecological health (Hochberg 2018). In the past, wildlife health was defined as the "absence of disease", which emphasizes backward-looking approaches that are reactive rather than approaches based on a proactive protection of health (Stephen 2014). Standardized and proactive approaches to manage wildlife disease are still relatively uncommon, despite widespread agreement that taking prevention and early action is likely more effective than triaging a large outbreak

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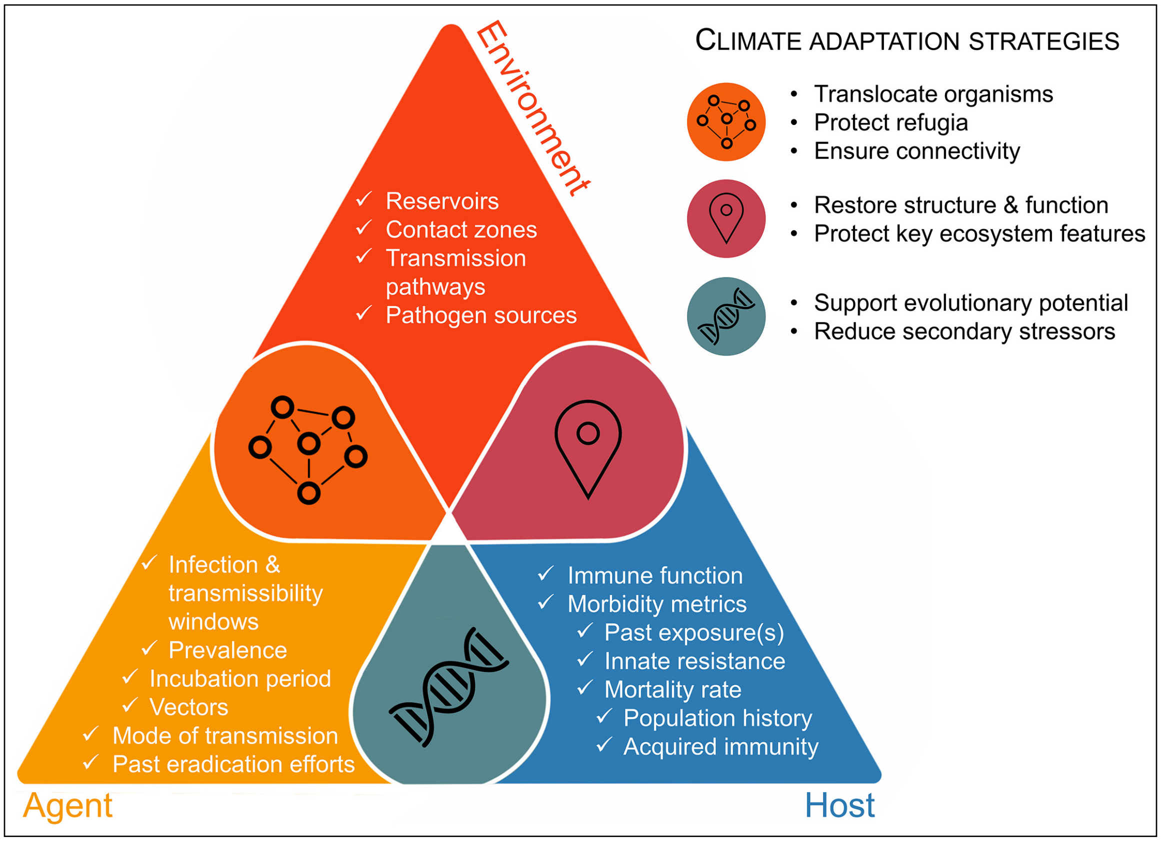

Figure 3. Key factors (denoted by check marks) for each component of the epidemiological triad (environment, host, and agent) that can be used to evaluate potential disease risks of the seven general adaptation strategies (listed at top-right corner), which operate at the nexus of each pair in the triad. For example, improving connectivity can affect transmission pathways and the prevalence of disease agents on the landscape. In general, environmental risk factors reflect the potential for disease spread. Host risk factors pertain to physiological and demographic parameters that affect population viability. Agent (pathogen) risk factors reflect the patterns and determinants of disease and can help identify climatic and disease refugia for the host.

(Langwig *et al.* 2015). Although changes in the dynamics of known pathogens can be evaluated, emergence of new pathogens is more difficult to foresee. Using a definition of health that goes beyond the "absence of disease" is one potential way for practitioners to shift practices toward maintaining health rather than responding to adverse outcomes, by considering the multifaceted biotic, abiotic, and anthropogenic determinants of health and resilience in wildlife populations (Stephen 2014). Taking a holistic, systems approach to identify both disease and non-disease determinants of health can help inform management action, especially when paired with strategic surveillance to support the early detection of possible threats and implementation of mitigation strategies.

Another approach to anticipating the potential impacts of adaptation actions on disease is to identify specific risk factors pertaining to the host, environment, and disease agent that can be assessed early in the planning phase to reduce unintended consequences (Figure 3). Specific guidance on conducting a thorough wildlife disease risk assessment is available from the International Union for Conservation of Nature and the World Organisation for Animal Health (formerly, Office International des Epizooties) (OIE and IUCN 2014), and covers such topics as hazard identification, option and consequence assessments, risk communication, contingency planning, and monitoring. When a lengthy or in-depth assessment is not needed or is unfeasible, proactively incorporating a checklist of disease risk factors in the planning phase can be a less resource-intensive way to evaluate potential unintended consequences and, ultimately, lead to better outcomes (Figure 3). For example, identifying existing transmission pathways for known pathogens or vectors on the landscape during the planning phase can help to determine if connectivity-oriented adaptation efforts will affect disease spread via creating, maintaining, or obstructing transmission pathways. For each proposed adaptation strategy, a rapid risk assessment can be conducted using the best available information to determine disease-related risks and to identify trade-offs among intervention options (Hopkins *et al.* 2022). Once categorized, "low-risk" adaptation actions can be prioritized for immediate implementation, whereas other actions characterized as "high-risk" but "high-reward" may—after trade-off analysis—warrant further deliberation or research.

Be flexible and evaluate uncertainty

The synergy of climate change and wildlife disease yields countless uncertainties that may impact a decision maker's

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willingness or ability to act. Thus, climate adaptation should be flexible and incorporate emerging information into decision making. Due to the long time horizons of many climate adaptation actions, the ability to learn from management and reassess objectives as conditions change is crucial (Cook *et al.* 2021). Developing flexible adaptation strategies that can accommodate change has frequently been proposed as a best practice, and as a way of addressing some of the uncertainties associated with climate change. The field of decision analysis offers a wide range of tools to help decision makers choose between acting in the face of uncertainty (eg structured decision making, decision trees, utility theory) or evaluating the benefit of reducing uncertainty (eg expected value of perfect information) *before* making decisions (Runge *et al.* 2011; Yoe 2019). When faced with uncertainty, it is tempting to choose no action or to maintain the status quo, particularly for practitioners or agencies that are risk averse. However, given all of the unknowns related to both climate change and wildlife disease, it is unlikely that any decision maker will have the luxury of resolving every uncertainty prior to implementation. Therefore, instead of being considered as a barrier to climate adaptation planning, uncertainty regarding disease impacts should be acknowledged openly, so that appropriate tools can be employed to manage it in the context of the decision-making process.

Assess indicators at regular intervals

Disease-related consequences of adaptation actions may not be immediately apparent because of the complexity of host–pathogen–environment interactions. To understand how near-term actions align with long-term implications, it is important to consider plausible impacts at multiple periods in the future and monitor for those impacts to inform future decisions. Having forward-looking and clearly articulated objectives and monitoring parameters is critical for ensuring that actions are both climate- and disease-smart. One approach is to use a formal adaptive management framework that balances management objectives with learning (Nichols *et al.* 2011). Although adaptive management has the potential to improve decision making by reducing uncertainty over time, it requires a substantial institutional commitment that can be difficult to sustain. However, even in the absence of this more formal approach, thoughtful monitoring can still improve decision quality when it occurs within a well-framed decision context. Having clear objectives and measurable indicators for desired near- or long-term outcomes—often called a "theory of change" (Margoluis *et al.* 2013)—is necessary to ensure that the data collected will improve subsequent decision making. For actions that are both climate- and disease-smart, this means anticipating outcomes that are both intended and unintended. When effectiveness measures are linked to a theory of change, the information can also help practitioners determine when conditions become conducive for pathogen introduction or spread, indicating the need for additional or altered interventions to lessen risk. To create a robust monitoring and evaluation framework, practitioners should develop a disease monitoring plan during the initial planning phases of an adaptation project and coordinate with climate-change experts and wildlife disease surveillance programs when possible. Identification of disease-smart approaches to climate adaptation that are feasible, impactful, and effective can be fostered through active communication and exchange of evidence-based information within and across agencies, policy makers, and the public.

Conclusions

Climate adaptation is an important and rapidly expanding field that offers decision support for practitioners to help species survive and adapt to novel and changing conditions. To meet this unprecedented challenge, practitioners will increasingly find themselves faced with taking actions that have substantial trade-offs, including weighing the benefits of climate adaptation against the risks of increased disease. Our intent is not to discourage adaptation initiatives, but rather to shine a light on potential unintended disease consequences and empower practitioners to anticipate and avoid negative outcomes. The tendency for disease outbreaks to complicate conservation efforts, both ecologically and sociopolitically, justify efforts to prevent climate adaptation actions from unintentionally exacerbating pathogen transmission or disease. By assessing risk, incorporating uncertainty, planning for change, and monitoring outcomes, it is possible to reduce disease-related consequences and improve adaptation outcomes.

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Data availability statement

No data were collected for this study.

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