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Climate Change and parasite Conservation: Balancing biodiversity and disease dynamics in Wildlife

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Abstract
The escalating climate crisis presents a profound paradox for wildlife conservation: while parasites are a significant part of Earth's biodiversity, they are also agents of disease whose dynamics are being fundamentally altered by environmental change. This review critically examines the intersection of climate change, parasite conservation, and wildlife disease ecology. We argue that traditional conservation paradigms, which often focus on eradicating parasites, are increasingly unsustainable in a warming world. Instead, we support a nuanced framework that distinguishes between parasites that require active conservation as essential components of ecosystem function and evolutionary history, and those posing emerging threats to wildlife populations under climatic stress. By synthesising recent literature, this article explores how climate change influences host-parasite interactions, including range shifts, phenological mismatches, and immune system modulation. We assess the conflicting conservation goals when a parasite is both a threatened species and a pathogen of concern. Through comparative case studies- from nematodes in Arctic ungulates to trematodes in amphibian systems- we emphasise the need for adaptive management strategies that incorporate ecological, evolutionary, and climatic data. Ultimately, this review proposes a roadmap for future research and conservation efforts, underscoring that a comprehensive approach to biodiversity must include the "unloved" majority parasites if we want to accurately predict and reduce the cascading effects of climate change on wildlife health and ecosystem resilience.

Keywords: Parasite conservation, climate change, wildlife disease, host-parasite dynamics, conservation conflict, ecosystem health

Introduction

The Anthropocene is characterised by the rapid, human-induced transformation of Earth's ecological systems, with climate change acting as a primary driver of biodiversity loss [1]. Conservation biology has traditionally concentrated on charismatic megafauna and keystone species, often neglecting the smaller, cryptic, and less popular components of biodiversity. Among these neglected elements are parasites, a diverse group of organisms including helminths, arthropods, protozoa, and fungi, which are estimated to comprise 40-50% of all described species [2]. For decades, the dominant conservation narrative has portrayed parasites solely as harmful agents- threats to be managed, controlled, or, in cases involving wildlife, eradicated to safeguard host populations [3]. However, this viewpoint overlooks a fundamental ecological truth: parasites are everywhere, and their presence is a natural part of functioning ecosystems. They influence host population dynamics, regulate food web structures, and act as reservoirs of genetic diversity [4]. Therefore, their loss signifies a significant, yet largely unseen, depletion of Earth's biotic heritage.

The conservation of parasites is therefore an emerging yet vital field, based on the understanding that biodiversity is incomplete without its parasitic component. Pioneering work by Windsor [5] and Gompper and Williams [6] laid the foundation by emphasising the intrinsic value of parasites, framing them as co-evolved partners with their hosts. More recent research has broadened this idea, suggesting that the loss of a host species inevitably leads to the co-extinction of its dependent parasites, representing a significant, yet unquantified, part of the current extinction crisis [7, 8]. This co-extinction cascade indicates that the true extent of biodiversity loss is much higher than what raw species counts of free-living organisms show.

Simultaneously, climate change is reshaping the rules of host-parasite interactions [9]. Rising global temperatures, altered precipitation patterns, and increased frequency of extreme weather events are not just adding pressure to already stressed systems; they are fundamentally changing the ecological context in which host-parasite relationships unfold [10, 11]. For parasites, climate change serves as a complex, multifaceted stressor. It can directly influence free-living life stages, such as eggs and larvae of many helminths, which are highly sensitive to temperature and moisture [12]. It can also modify the geographic distribution of both hosts and parasites, resulting in new assemblages and the emergence of diseases in previously unexposed populations [13]. Moreover, climate-induced stress can weaken host immunity, leading to immunocompromised populations that are more vulnerable to both endemic and new parasites [14].

This convergence of a new conservation ethic that values parasite biodiversity and a global environmental crisis that destabilises host-parasite systems presents a profound intellectual and practical challenge. How do we simultaneously promote the conservation of parasite diversity while addressing the disease threats that climate change worsens? This is the central paradox of parasite conservation in the 21st century. A parasite that is a rare, endemic species with a narrow host range and thus a candidate for conservation may, under changing climatic conditions, expand its range, encounter a new, vulnerable host, and become a pathogen of significant concern [15]. Conversely, a common, generalist parasite that is usually harmless might, under climatic stress, become a major factor in host population decline [16]. Conservation goals are not fixed; they are dynamic and context-dependent.

This review aims to explore this complex landscape. We start by providing a detailed literature review that synthesises the current understanding of the ecological roles of parasites and how climate change influences host-parasite interactions. We then critically examine the conflicts involved in managing parasites under changing climate conditions, offering comparative frameworks to aid decision-making. Through a series of case studies, we demonstrate real-world examples of this conservation dilemma. Finally, we propose an integrated, adaptive framework for parasite conservation and disease management in an era of rapid climate change, highlighting the importance of predictive modelling, long-term monitoring, and a fundamental shift in conservation philosophy. By embracing the complexity of these relationships, we can move beyond a simplistic "good vs. evil" perspective on parasites and develop a more nuanced, resilient approach to biodiversity conservation in a warming world.

The Multifaceted Role of Parasites in Ecosystems and the Threat of Co-extinction

To thoughtfully debate the conservation of parasites, one must first move beyond the anthropocentric view of parasites as solely harmful organisms. Increasingly, ecological literature shows that parasites are crucial to ecosystem structure, stability, and function [4, 17]. Their roles are varied and often surprising. For example, parasites can influence competitive interactions between host species. A well-known example is how nematode parasites help different rodent species coexist; by disproportionately impacting the dominant species, parasites can prevent competitive exclusion and help maintain species diversity [18]. Similarly, parasites can influence predator-prey relationships by altering prey behaviour or condition, making prey more vulnerable to predators, thereby helping stabilise food webs [19, 20].

Furthermore, parasites constitute a significant portion of the biomass and energy flow in ecosystems [21]. In many aquatic and terrestrial systems, the biomass of parasitic nematodes, trematodes, and cestodes matches or exceeds that of top predators [22]. They help with nutrient cycling by affecting host metabolism and mortality, effectively moving nutrients from host tissues back into the environment. Parasites also serve as a hidden food source for other organisms, with many predators, such as cleaner fish and certain bird species, purposely eating parasitised prey [23]. Removing parasites from an environment, therefore, can lead to cascading and unpredictable effects.

This recognition has led to the concept of "co-extinction," which suggests that the extinction of a host species will cause the extinction of its obligate parasites [7, 8, 24]. This is not just a theoretical issue. In an analysis of host-parasite networks, Colwell et al. [24] estimated that for each host species that goes extinct, between one and three dependent parasite species are likely to be lost. Because many parasitic groups are highly host-specific, especially in stable, long-evolved systems like those in tropical rainforests, the risk of co-extinction is significant [25]. Dunn et al. [7] also argued that parasites and other dependent species might be more vulnerable to extinction than their hosts, as they face both host population decline and the direct effects of environmental change.

However, conserving parasites faces challenges beyond those posed by ecological theory. There is a significant "taxonomic bias" and "charisma bias" in conservation science [26]. Parasites, especially endoparasites like flatworms and nematodes, lack the public appeal of pandas or whales. They are often seen as disgusting, dangerous, or simply unimportant. This view influences research funding and policy, leaving parasite conservation heavily underfunded. A comparison of conservation funding over the past two decades highlights this gap (Table 1).

Table 1: Comparative Analysis of Conservation Funding and Research Output for Vertebrates vs. Parasites (2000-2023)

Taxonomic Group	Estimated No. of Species [2, 27]	Average Annual Conservation Funding (USD, millions) [28]	Peer-Reviewed Articles on Conservation (2000-2023) [29]	% of Species with IUCN Assessment [30]
Mammals	~6,500	$1,200	~85,000	100%
Birds	~11,000	$900	~92,000	100%
Amphibians	~8,700	$180	~28,000	85%
All Parasites	~300,000 - 1,000,000+	< $10	~2,500	< 0.1%

*Data synthesised from [2, 27-30]. *

This table clearly highlights the neglect of conservation. While most mammal and bird species have been evaluated by the International Union for Conservation of Nature (IUCN), less than 0.1% of described parasite species have undergone any conservation status assessment [30]. This lack of data causes a fundamental problem: we cannot conserve what we have not catalogued, understood, or deemed worth protecting. The few parasites that have gained attention are often large, charismatic (e.g., the California condor louse, *Colpocephalum californici,* which was controversially delisted), or those that pose a significant threat to commercially or culturally important species [31].

The risk of losing this unseen biodiversity is not simply about aesthetics or completeness. The extinction of a parasite can result in the loss of its unique evolutionary history, genetic resources (which may have biomedical or pharmacological importance), and its functional role within the ecosystem [32, 33]. For instance, the disappearance of a parasite that controls a dominant host population could, in theory, cause unchecked growth in that host and lead to ecosystem degradation. As we confront the climate crisis, we must evaluate whether our historical neglect of parasite conservation has left us unprepared to understand and manage the complex, emerging host-parasite systems [34].

Mechanisms of Climate-Driven Change in Host-Parasite Dynamics

Climate change affects host-parasite interactions through a complex network of direct and indirect mechanisms. Understanding these processes is essential for predicting which parasite-host systems might become unstable and for creating effective conservation and management strategies. These influences can be divided into three main pathways: (1) direct effects on parasite life cycles and physiology, (2)

indirect effects through changes in host biology and immunity, and (3) modifications to the broader ecological context, such as shifts in species ranges and timing (phenology).

3.1. Direct Effects on Parasite Transmission and Survival

Many parasites, especially those with free-living stages (e.g., trematode cercariae, nematode larvae), are poikilotherms, meaning their development, survival, and activity depend directly on ambient temperature and moisture [12, 35]. For macroparasites such as gastrointestinal nematodes, the time required for development from egg to infective larva (L3) varies with temperature and is a key factor influencing transmission potential. In a warming climate, this development period often shortens, leading to shorter generation times and potentially increased parasite load on hosts [36]. However, this relationship is not always straightforward. Extreme temperatures can surpass thermal tolerances, increase mortality rates and ultimately reduce transmission [37]. Generally, this relationship is unimodal, with an optimal temperature range for successful transmission.

Precipitation is another essential direct factor, especially for parasites with life stages vulnerable to drying out. In dryland ecosystems, less rainfall can significantly decrease the survival of free-living nematode larvae on pasture, reducing transmission [38]. Conversely, more rainfall or higher humidity can create favourable microclimates for egg hatching and larval survival, possibly leading to outbreaks [39]. The interplay between temperature and moisture is crucial, with climate models predicting changes in both that will result in highly variable, region-specific effects on parasite transmission dynamics.

3.2. Indirect Effects Through Host Susceptibility and Immunity

Climate change can indirectly influence parasite dynamics by weakening host health and immunity. Environmental stresses such as heat waves, droughts, or food shortages can induce a physiological stress response in wildlife, characterised by elevated glucocorticoid levels [14, 40]. Long-term elevation of these stress hormones is known to suppress the immune system, thereby increasing host vulnerability to both existing and novel parasites [41]. A meta-analysis by Lafferty and Kuris [9] shows that, in most studied systems, climate-related stressors correlate with higher disease prevalence, often through immune suppression. This impact is especially strong in populations already fragmented or diminished by habitat destruction, where genetic diversity, including immune genes such as the Major Histocompatibility Complex (MHC), is lowered [42]. Furthermore, shifts in host nutritional status caused by climate-altered food webs can affect immunity. For example, in the Arctic, climate change is changing the quality and availability of forage for caribou and muskoxen, leading to nutritional stress [43]. Hosts with poor nutrition are less able to mount effective immune responses to gastrointestinal nematodes and other parasites, resulting in higher worm burdens and increased pathogenicity [44]. This interaction among environmental stress, host condition, and immunity creates a positive feedback loop in which climate change makes hosts more vulnerable to parasitic diseases.

3.3. range Shifts, Phenological Mismatches, and Novel Assemblages

Perhaps the most significant ecological impact of climate change is the redistribution of species. As temperatures increase, many species are moving their geographic ranges toward the poles or higher elevations [45, 46]. Parasites, like their hosts, are also experiencing such range shifts, but often at different rates. A parasite with a short generation time and high dispersal ability might colonise new regions much faster than its historical host, resulting in its establishment in naive host populations that have not co-evolved resistance [13]. This scenario creates a risk for disease emergence.

Alternatively, a host may expand its range more rapidly than its parasites, leading to "enemy release" a temporary period during which the host is free from its natural parasites, potentially enabling it to become an invasive species [47]. This phenomenon has been observed in various systems, from insects to plants. The new geographic ranges can also result in novel host-parasite assemblages, where parasites encounter hosts with which they have no co-evolutionary history. The outcome of such encounters is highly unpredictable, ranging from low pathogenicity to catastrophic disease outbreaks [48].

Phenological shifts, alterations in the timing of seasonal life cycle events, are another vital consequence of climate change. In host-parasite systems with synchronised life cycles, a mismatch can be harmful. For instance, many migratory birds arrive at their breeding grounds only to find that the peak emergence of their arthropod vectors (e.g., ticks) no longer coincides with their nesting period [49]. This phenological mismatch can decrease parasite transmission, providing a natural reprieve. Conversely, a mismatch in which parasites emerge earlier or persist later in the season can increase exposure. For parasites with complex, multi-host life cycles, climate-driven changes in the phenology of different host species can either disrupt or enhance transmission in intricate ways [50].

Table 2: Summary of Key Climate Change Mechanisms Affecting Host-Parasite Systems

Mechanism	Direct/Indirect	Effect on Parasite Transmission	Example System	Reference {s)
Increased Temperature	Direct	Accelerated development of free-living stages; increased transmission (within thermal limits)	GIN* in domestic and wild ruminants	[36, 37]
Altered Precipitation	Direct	Decreased survival in dry conditions; increased survival in moist conditions	Free-living larvae of *Ostertagia* spp.	[38, 39]
Host Nutritional Stress	Indirect	Immunosuppression; increased parasite burden and pathogenicity	Arctic ungulates (*Ovibos moschatus*) and nematodes	[43, 44]
Host Stress (Glucocorticoids)	Indirect	Immunosuppression; increased susceptibility to infection	Various; reviewed in	[14, 41]
Range Shifts	Indirect	Parasite invasion of naïve host populations; enemy release for hosts	*Parelaphostrongylus tenuis* and moose (*Alces alces*)	[13]
Phenological Mismatch	Indirect	Decoupling of host and parasite life cycles; increased or decreased transmission	Avian hosts and their arthropod vectors	[49, 50]

*GIN: Gastrointestinal nematodes.

The Conservation Conflict: When to Protect and When to Manage

The main argument of this review is that climate change demands a critical reassessment of our conservation priorities concerning parasites. The traditional perspective that all parasites are nuisances to be eradicated is ecologically flawed and not feasible in practice. In contrast, the emerging perspective that all parasites are important parts of biodiversity to be preserved is equally challenging when confronted with a climate-induced disease crisis. The key is to create a decision-making framework that, on a case-by-case basis, can determine whether a parasite should be targeted for conservation or disease control [15, 51].

A primary consideration is the difference between co-evolved, stable parasites and emergent or invasive parasites. Co-evolved parasites, often exhibiting high host specificity, have likely been part of a host's evolutionary landscape for millennia. Their impact on host populations is often subtle, contributing to the natural ebb and flow of host numbers without causing extinction [4]. These parasites, especially those with narrow host ranges that are themselves threatened, are prime candidates for conservation [24]. Their extinction would represent a genuine loss of co-evolved biodiversity and a severing of evolutionary links.

In contrast, emergent parasites, especially generalists, pose a different challenge. Climate change is aiding their spread into new areas where they can cause devastating effects [13]. A well-known example is the meningeal worm (*Parelaphostrongylus tenuis*), a nematode native to white-tailed deer (*Odocoileus virginianus*) in eastern North America. As climate change promotes the northward expansion of white-tailed deer, it also introduces this parasite into the ranges of moose (*Alces alces*), a species with which it has no co-evolutionary history [13, 52]. In moose, *P. tenuis* causes severe neurological disease (moose sickness) and contributes significantly to population declines in some areas. From a conservation standpoint, *P. tenuis* is a native, common species in one host (deer), but a destructive pathogen in another (moose). The primary concern is not its conservation but how to manage its impact under a changing climate.

Another critical factor is the parasite's functional role. Is it a keystone species that shapes the community? Or is it a passenger, present without significant ecological impact? A keystone parasite, like the trematode *Euhaplorchis californiensis* in California salt marshes, manipulates the behaviour of its intermediate host (killifish), making them more vulnerable to predation by the definitive host (birds) [19]. This parasite is a key node in the food web, connecting fish to birds and affecting energy flow. Its removal would likely change the entire ecosystem. Such a parasite deserves a different conservation status than a generalist parasite that is simply an incidental passenger [20].

The host's conservation status is also crucial. The same parasite can have very different effects depending on its host. A parasite that is harmless in a common, widespread host may pose a serious threat to a small, fragmented, and endangered host population [53]. The relationship between host vulnerability and parasite impact is at the heart of the conservation conflict.

Table 3: A Framework for Categorising Parasites under Climate Change

Category	Characteristics	Example	Climate Change Effect	Conservation/Management Action
Co-evolved Specialist	High host specificity; stable host-parasite relationship; may have a narrow geographic range	*Colpocephalum californici* (Condor Louse)	A range shift of the host could lead to co-extinction or host-parasite decoupling.	Conservation Priority. Consider host-based conservation, assisted colonisation of the parasite if the host is translocated.
Keystone Parasite	Exerts a strong regulatory effect on the host population or food web structure	*Euhaplorchis californiensis* (Trematode)	Altered temperatures could disrupt the complex life cycle; loss could lead to ecosystem instability.	Conservation Priority. Monitor critical life stages; ecosystem-based management.
Emergent Pathogen	Generalist; novel to host; causes high morbidity/mortality; range expanding due to climate	*Parelaphostrongylus tenuis* (Meningeal worm)	Range expansion into naïve host populations (e.g., moose).	Disease Management Priority. Active surveillance, host population management, and potential for targeted interventions.
Climate-Exacerbated Pathogen	Endemic; typically benign, but becomes pathogenic under host climate stress	*Ostertagia gruehneri* (Nematode) in Arctic caribou	Warming accelerates larval development and increases host nutritional stress, increasing the burden and pathogenicity.	Integrated Management. Monitor host body condition and parasite loads; manage for host resilience (e.g., habitat protection).

This framework (Table 3) is not a strict classification but a tool to guide thinking. It highlights that the same parasite species can be classified differently depending on the host population and environmental context. Conservation and management responses must be similarly adaptable and context-specific.

Case Studies in the Climate-Parasite Conservation Nexus

To ground this theoretical discussion in reality, it is instructive to examine specific systems where climate change, parasite dynamics, and conservation concerns intersect.

5.1. Case Study 1: The Arctic Ungulate – Nematode System

The Arctic is warming at nearly four times the global average, making it a sentinel region for climate-driven ecological change [54]. In this system, the relationship between caribou (Rangifer tarandus), muskoxen (*Ovibos moschatus*), and their gastrointestinal nematodes (e.g., *Ostertagia gruehneri, Marshallagia marshalli*) is being fundamentally altered. Historically, these host-parasite systems were considered stable. However, warming temperatures are predicted to accelerate the development of free-living nematode larvae on the tundra, leading to earlier and more intense peaks of infective larvae in the environment [36, 55]. At the same time, climate change is

degrading the quality and availability of forage, causing nutritional stress in host populations [43].

The combined effect is a climate-exacerbated pathogen scenario (Table 3). Nutritionally stressed hosts are less able to mount effective immune responses, allowing them to carry higher worm burdens [44]. High burdens of *O. gruehneri* have been linked to reduced fecundity and increased mortality in caribou [56]. The conservation conflict here is not whether to conserve the nematodes, which are common and widespread, but how to manage the system to maintain host population resilience. Strategies focus on preserving critical foraging habitat to mitigate nutritional stress, rather than attempting to eliminate the parasites [57]. This represents a paradigm shift from parasite control to ecosystem-based management that promotes host-parasite balance.

5.2. Case Study 2: Amphibian Chytridiomycosis and the Global Amphibian Decline

The emergence of the chytrid fungi Batrachochytrium dendrobatidis (Bd) and *B. salamandrivorans* (Bsal) has caused the most devastating disease-driven loss of biodiversity ever recorded, leading to the decline or extinction of hundreds of amphibian species [58]. While Bd is now globally distributed, its emergence and spread are closely linked to globalisation and trade, but climate change is now influencing its dynamics [59]. Warming temperatures can change the distribution of Bd by making previously unsuitable, cooler high-elevation habitats more favourable for the fungus [60]. Conversely, in some regions, warming temperatures may push Bd beyond its thermal optimum, offering refugia for amphibians [61]. The relationship is complex and varies by region.

From a conservation perspective, this case presents a significant challenge. Bd is a parasite and pathogen that has caused the extinction of multiple species. There is no question about conserving Bd; it is a management target. However, the response to Bd has itself sparked a debate about parasite conservation ethics. Ex situ conservation programs, captive breeding, and antifungal treatments have been used to save species such as the Panamanian golden frog (*Atelopus zeteki*) [62]. These actions prioritise the host's survival, a charismatic vertebrate, over that of the parasite. The debate becomes more nuanced when considering less virulent strains of Bd that may have co-evolved with certain host species. In such cases, could management interventions (e.g., treating the host) disrupt a stable co-evolutionary relationship? This case highlights the difficulty of applying a universal ethic; the parasite's virulence and impact are the main factors guiding the conservation response [63].

5.3. Case Study 3: Vector-Borne Diseases in a Warming World

Climate change is widely expected to expand the geographic range and lengthen the transmission season of many vector-borne diseases [64]. Ticks, mosquitoes, and other arthropod vectors are highly affected by temperature and humidity. The northward spread of the black-legged tick (Ixodes scapularis) and the associated pathogen Borrelia burgdorferi (Lyme disease) in North America is one of the most well-documented examples [65]. For wildlife, this has significant consequences. The moose-winter tick (*Dermacentor albipictus*) system is another important case. Winter ticks are native parasites of moose, but climate change is causing earlier snowmelt and longer autumns, which extend the period during which larval ticks can quest for hosts [66]. This has led to hyper-infestation events, with individual moose carrying tens of thousands of ticks, resulting in anaemia, hair loss, and death, and contributing to population declines in parts of the northern United States [66].

The conservation dilemma here is complex. The winter tick is a native parasite, but its behaviour is being drastically changed by climate, turning it into a major threat to a host species (moose) that holds significant ecological, cultural, and economic value. Management strategies under consideration include using acaricides on moose or altering tick habitat, but these measures raise concerns about unintended effects on other species and the broader ecosystem [67]. This situation challenges the idea that a' natural" native parasite can become a conservation issue when environmental conditions change.

Future Directions: Towards an Integrated, Adaptive Framework

The previous analysis shows that navigating the intersection of climate change and parasite conservation requires moving beyond simple, static management methods. We suggest an integrated, adaptable framework based on three pillars: (1) improved surveillance and predictive modelling, (2) a detailed, context-specific conservation ethic, and (3) collaboration across disciplines.

1. Enhanced Surveillance and Predictive Modelling

A key challenge in this field is the lack of baseline data. We have an incomplete record of parasite biodiversity, a limited understanding of most host-parasite systems, and inadequate long-term monitoring programs [26, 30]. To advance, we need to invest in long-term ecological monitoring that specifically tracks host and parasite populations along with climate variables. This data is crucial for developing predictive models. For example, mechanistic niche models that include the physiological tolerances of free-living parasite stages, host immunity, and dispersal abilities are more reliable than correlative models for predicting future disease risks [68]. These models can help identify "hotspots" of parasite emergence and "refugia" for vulnerable host populations. Progress in environmental DNA (eDNA) and metabarcoding provides promising options for quick, non-invasive assessment of parasite diversity in ecosystems, offering a more complete view of the hidden biodiversity at risk of loss [69].

2. A Nuanced, Context-Specific Conservation Ethic

The conservation community must adopt a more nuanced ethic towards parasites. This involves moving beyond the binary of "protect all" or "destroy all" and embracing a triage approach that considers the parasite's evolutionary history, ecological role, and threat level within the context of climate change [15, 51]. This ethic should be codified in policy. We recommend expanding the IUCN Red List criteria to include the conservation status of parasites, possibly through a new category or a "dependent species" classification [7, 8]. This would compel conservation practitioners to consider the threat of co-extinction. Additionally, conservation plans for threatened host species should explicitly incorporate parasite management strategies. If a host is translocated, what becomes of its parasite community? Is the translocation of a co-evolved,

non-threatening parasite a conservation success, or is the goal a "sterile" host? These are questions that require explicit answers [70].

3. Cross-Disciplinary Collaboration

The challenges outlined in this review cannot be solved by ecologists or parasitologists alone. They require genuine collaboration across disciplines. This includes:

- **Climate Scientists:** To provide downscaled, high-resolution climate projections that can be integrated into biological models.
- **Wildlife Veterinarians and Disease Ecologists:** To develop safe and effective interventions for managing disease outbreaks when necessary, while minimising impacts on non-target parasites.
- **Conservation Geneticists:** To assess the adaptive potential of hosts and parasites to climate change, and to identify populations with high genetic diversity that may be more resilient [42].
- **Social Scientists and Ethicists:** To help navigate the complex ethical dilemmas that arise when conservation goals conflict. Public engagement is also crucial; shifting the narrative from "parasites are gross" to "parasites are a vital part of our natural heritage" will be essential for building support for their conservation [26].

Finally, the framework must be adaptable. As the climate continues to change and our understanding deepens, management goals will need to be revised. What is a conservation priority today may become a disease threat tomorrow, and vice versa. Rigorous monitoring, transparent evaluation of management outcomes, and a willingness to change course are essential elements of this adaptive approach [71].

Conclusion

The intersection of climate change and parasite conservation is one of the most complex and intellectually challenging areas in modern ecology. For too long, conservation biology has operated under a paradigm that favours free-living and charismatic species, neglecting the parasitic majority that makes up a significant part of Earth's biodiversity. This review argues that this historical neglect is no longer acceptable. The climate crisis acts as a powerful catalyst, forcing us to confront the paradox that the same parasites we may wish to conserve for their evolutionary and ecological value can, under changing environmental conditions, become potent agents of disease threatening the very host populations we aim to protect.

We have synthesised extensive literature showing that climate change disrupts host-parasite systems through various interconnected mechanisms, including direct effects on parasite life cycles, indirect effects on host immunity, and the large-scale reorganisation of species ranges and phenologies. This results in a global ecological landscape characterised by novel host-parasite assemblages, emerging disease outbreaks, and the risk of parasite co-extinction. In this dynamic context, rigid conservation frameworks are bound to fail. The key point is that there is no single, universal answer to whether to conserve or control a parasite. The decision depends on a complex interplay of the parasite's life history, ecological role, host vulnerability, and the specific climate trajectory in that system.

This review proposes a nuanced, integrated, and adaptable approach moving forward. We must invest in fundamental research on parasite biodiversity to document these invisible species before they are lost. We need to develop and improve predictive models to anticipate climate-driven changes in parasite dynamics, thereby enabling proactive rather than reactive management. Most importantly, we must adopt a new conservation ethic that recognises parasites as legitimate conservation targets, while maintaining the capacity for decisive action when parasites threaten biodiversity. This ethic should be embedded in policy by expanding frameworks such as the IUCN Red List to include co-extinction risks and by integrating parasite management into conservation plans for threatened hosts.

The conclusion of this review is a call for more mature conservation thinking. To protect biodiversity in a rapidly changing world, we must shed simplistic biases and embrace the full, messy complexity of nature. This includes valuing the tapeworm as we do the tiger, not because they are the same, but because they are interconnected in a web of life under unprecedented pressure. A holistic view of ecosystem health encompassing all biodiversity, including its most unloved members, is not just an academic ideal; it is a practical necessity. Only by understanding and managing the entire spectrum of life, from the largest mammal to the smallest protozoan, can we hope to build resilient ecosystems capable of withstanding the significant challenges of the Anthropocene. The future of wildlife conservation will depend not only on protecting charismatic species but also on our wisdom in managing the intricate, parasitic relationships that fundamentally support the health and functioning of the natural world.

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