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PARASITE CONSERVATION, CONSERVATION MEDICINE, AND ECOSYSTEM HEALTH

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Conservation medicine links disparate fields of study to understand the underlying causes of ecological health problems and the ecological context of health (Tabor 2002). Often this requires analyzing complex and highly interlinked processes that are seldom well understood. The causes and consequences of changes in parasite biodiversity represent an important but overlooked aspect of conservation medicine. In this chapter we explore the quandary presented by parasites: this diverse suite of organisms threatens the health of individuals and populations but is nonetheless critical for maintaining healthy ecosystems (Hudson et al. 2006).

Parasites[1] appropriate host resources to feed and/or to reproduce, lowering host fitness (albeit at widely varying degrees) through effects on physiology, morphology, and/or behavior. Parasites can cause mortality and severe morbidity, including disability and nutritional, growth, and cognitive impairments, and affect food production, economic trade, and biodiversity conservation. As a consequence, and for good reason, the stance of the medical sciences towards parasites is best characterized by direct antagonism. Indeed, some of the greatest achievements in medical history have been the extirpation or eradication of pathogenic organisms. However, parasites are ubiquitous, and their effects on the overall functioning of ecosystems are complex and often positive.

Until recently, within the field of ecology, parasites have been overlooked as unimportant to the maintenance of viable ecosystems, perhaps due to their cryptic nature, intractably high diversity, small size, patchy distribution, and a general lack of observable morbidity in nature. Similarly, within conservation biology, practitioners and academics are more prone to evaluate the role of parasites as threats to host populations than to discuss the need for conserving host–parasite relationships (Gompper and Williams 1998). This may come as little surprise in a field long plagued by taxonomic biases, in which invertebrates, fungi, and microscopic organisms have historically received the least attention.

It is within this mixture of open antipathy, disregard, and lack of knowledge and awareness that parasite biodiversity is most often viewed today. However, over the past two decades, several lines of research have highlighted the critical importance of parasite biodiversity to the central goals of both

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[1] Here we use the term "parasite" to refer to macro and microparasite taxa. We do not consider nest parasites or parasitoids in this chapter.

conservation biology (the long-term maintenance of biodiversity) and conservation medicine (maintaining ecological health). The numerical dominance of parasites in ecosystems and their roles in ecological and evolutionary processes suggest a critical need for explicit attention to parasite conservation. This task is both important and challenging. As parasites are deleterious for their host, they have the potential to negatively affect the conservation of biodiversity (Cunningham and Daszak 1998; Leendertz et al. 2006). To conserve parasites is to explicitly conserve morbidity and mortality in host populations. This is not a charge to take lightly, but it is likely a necessary step towards the conservation of overall ecosystem integrity.

This chapter outlines the current state of parasite conservation. We make a general case for *why* parasite conservation should be considered by briefly covering the contributions of parasites to ecosystems in both ecological and evolutionary time. To discuss *how* parasite conservation is currently achieved, we focus on the few existing parasite-focused conservation strategies, and offer some suggestions on how such strategies could be implemented. Finally, we highlight some of the challenges and conflicts that will likely arise in the implementation of such strategies.

WHY CONSERVE PARASITES?

As with all biodiversity, the overarching drive to conserve parasite species or host–parasite interactions can be outlined in terms of utilitarian or intrinsic value arguments. Utilitarian arguments are invoked to engender support for the conservation of functions that result in benefits for human health and well-being, and as a means to quantify the potential losses (e.g., in economic or in quality of life metrics) that could result from biotic impoverishment. The scientific literature has shed light on the functional importance of parasites at different spatial and temporal scales. Much has been written about the importance of parasite biodiversity to ecosystem structure and function (Marcogliese 2004; Thompson et al. 2005; Christe et al. 2006; Lefevre et al. 2009); their role in the evolution of complex structures, mechanisms, and behaviors through evolutionary time (Loehle 1995; Wegner et al. 2003; Blanchet et al. 2009); and their ability to inform our understanding of ecology and evolution (Whiteman and Parker 2005; Nieberding and Olivieri 2007). In the following sections we highlight some of these roles, as well as ecosystem services mediated by parasites.

Any dialogue about biodiversity conservation is incomplete without mention of intrinsic value. Ethical, moral, and aesthetic arguments for conserving parasites are equally strong as those invoked for the conservation of their hosts (Daszak and Cunningham 2002). Eloquent discussions of this issue are provided by Gompper and Williams (1998) and Windsor (1997, 1998a, 1998b).

PARASITE DIVERSITY

Of the approximately 42 recognized phyla, nine are entirely parasitic, 22 are predominantly parasitic, and most of the remaining have multiple parasitic clades (Poulin and Morand 2000; DeMeeûs and Renaud 2002). Recent studies estimate that parasitic helminths alone are about twice as speciose as their vertebrate hosts (Poulin and Morand 2000; Dobson et al. 2008) (Table 6.1). Estimating global parasite diversity remains challenging; current estimates do not yet incorporate most host taxa and focus only on macroscopic parasites, most vertebrates are inadequately sampled for parasites, and many of the parasite species upon which these estimates are based are likely to represent clusters of cryptic species (Poulin and Morand 2004; Dobson et al. 2008). Notably, microscopic parasitic diversity is also vast (Angly et al. 2006; Cotterill et al. 2008).

Overall, while we know that parasites outnumber free-living species, much of parasite biodiversity, which includes an astonishing variety of taxa, morphologies, life histories, and transmission modes, remains largely unknown. This non-monophyletic group also spans broad variation in the magnitude and direction of effects on individuals, host populations, and ecosystems, such that the overall effect of parasitism in one ecosystem or in a particular function can be quite different in another (Lafferty 2008). Therefore, while generalizations about the functional relevance or threat levels of parasite biodiversity are difficult, we suggest that common perceptions of parasites severely overlook relevance and underestimate threat.

Table 6.1 Summary of Parasite-Mediated Functions Associated with Actual or Potential Benefits for Hosts

Category	Function
Ecosystem organization	
	Regulation of host distribution and abundance
	Maintenance of food web structure
	Mediation of competitive interactions and apparent competition
	Regulation of parasite community
	Ecosystem engineering
	Nutrient and energy cycling
Benefits to hosts	
	Modulation of host immune response (hygiene hypothesis)
	Provision of molecules and biochemical processes
	Sentinels species for environmental stress
	Accumulation of heavy metals
Information sources	
	Biodiversity and environmental indicators/sentinels
	Host ecology, ontogeny, and phylogeny
	Ecological models

PARASITES AND ECOSYSTEMS

Beyond their preponderance in global biodiversity estimates, within individual ecosystems, parasite biomass can surpass the biomass of other much larger-bodied groups and dominate food webs (Suttle 2005; Lafferty et al. 2006). Recent research has shown that food webs contain on average more parasite–host links than predator–prey links (Lafferty et al. 2008). This sheer abundance confers a remarkable role in maintaining a “cohesive matrix” of interactions within food webs (Lafferty et al. 2006). While our theoretical understanding of these relationships remains broadly based on free-living organisms, empirical evidence demonstrates a positive influence of parasites on food web connectance: the percent of a food web’s realized resource use links (Lafferty et al. 2006). Connectance has empirical and theoretical positive relationships with food web stability (Dunne et al. 2002; Lafferty et al. 2006) and is positively associated with food web robustness in the face of secondary extinctions (Bascompte and Jordano 2007; Dunne and Williams 2009).

We now understand parasites as major drivers of ecosystem organization, capable of shaping community and ecosystem ecology (Hudson et al. 2006; Holdo et al. 2009). Parasites can influence host distribution across all spatial scales. For example, within a single water column, trematodes (*Microphallus papillorobustus*) effectively split populations of their gammarid shrimp (*Gammarus insensibilis*) hosts by causing infected individuals to live closer to the surface than their uninfected counterparts (Ponton et al. 2005); at a continental scale, trypanosomiasis has long had a role in determining the distribution of humans and animals in Africa (Knight 1971; Rogers and Randolph 1988). Parasites can also affect host abundance in a variety of ways. Direct mortality from infection can modulate host abundance, but sub-lethal infection can also result in changes in host population size, for instance by altering host susceptibility to predation (Mouritsen and Poulin 2003). Parasites can lower host and/or vector populations by causing altered sex ratios, lowered reproductive output, infertility, or abortion. In the most extreme case, parasitic castrators will prevent the host from reproducing altogether. The host then becomes the parasite's "extended phenotype": the parasitized host is removed from the gene pool and its metabolic output will only contribute to the parasite's reproduction (Lafferty and Kuris 2009).

Overall, parasites play significant roles in mediating species coexistence, community composition, and species diversity across space and time (Mouritsen and Poulin 2005; Freckleton and Lewis 2006; Wood et al. 2007). Many parasites have differential effects on sympatric host species, becoming the modulators of direct and apparent competition (situations in which the presence of one species lowers another's fitness through the presence of a shared enemy) outcomes. Models suggest that the replacement of the native red squirrel (*Sciurus vulgaris*) by the introduced gray squirrel (*S. carolinensis*) in the United Kingdom has been driven by apparent competition mediated by a parapoxvirus (Tompkins et al. 2003). These effects are not limited to free-living species: parasites can affect the host's morphology and immunological landscape, thereby altering its suitability for other parasite species, both promoting and inhibiting parasite coexistence (Thomas et al. 2005; Jolles et al. 2008; Lefevre et al. 2009)

Often these modulating roles of parasite activity translate to large effects on energy transfer across ecosystems. In some cases, parasites manipulate host behavior to increase their (the parasites) predation risk, thereby promoting increased transfers of matter and energy between different compartments within an ecosystem (Kuris 2005). For example, infection with a nematomorph worm (*Paragordius tricuspidatus*) induces crickets (*Nemobius sylvestris*) to commit "suicide" by jumping into water (Thomas et al. 2002); in the absence of the parasite, the trophic interactions that complete the transmission cycle in the water would not take place. Also, recent research has shown that viruses are critical players in global geochemical, nutrient, and energy cycles. Marine viruses kill an estimated 20% of the total oceanic bacterial biomass each day, and the resultant movement of matter from living organisms to dissolved nutrient pools ultimately channels as much as 25% of the ocean's primary production (Suttle 2007), as well as respiratory rates, productivity, and the physical-chemical properties of sea water (Suttle 2005). Future research will undoubtedly uncover further additional parasite effects on ecosystem processes.

PARASITES AND EVOLUTION

Parasitic organisms have also played a large role in the evolutionary processes of their hosts. Some of the classic examples of this are the "arms races" that occur between parasites and hosts, with genetic changes in one species resulting in a selective pressure on the other species, which then evolves as well. This general phenomenon has been termed the "Red Queen" hypothesis, after Lewis Carroll's character that must always keep running "just to keep in the same place." For example, *Microphallus* trematode parasites in New Zealand ponds track the genotypes of their *Potamopyrgus* snail hosts (Lively 1989). Parasites also have contributed to the maintenance of sexual reproduction in their hosts (as opposed to clonal reproduction, which would leave twice as many daughters as those produced in a biparental population), via the advantage that rare genetic variants, produced from recombination, have in environments where there are parasites. This has been observed in nature in both the same snail species described above (Lively 1987; Jokela et al. 2009) and in topminnow fish (*Poeciliopsis monacha*) (Lively et al. 1990).

The presence of parasites has also clearly shaped other components of the evolutionary pathways of their hosts. Guralnick et al. (2004) showed that large species of *Cyclocalyx* clams were more than 12 times more likely to be parasitized by allocreadiid trematodes than small species and postulated that tradeoffs between reproductive output and risk of parasitism may have resulted in numerous transitions in body size in the evolutionary diversification in this group of hosts. A similar trend has been observed in fish with parasites imposing selection pressures on their hosts to mature at a smaller body size (Morand 2003). Diverse parasites may have also shaped fundamental physiological properties of organisms. Morand and Harvey (2000) showed a significant positive correlation between parasite richness and the basal metabolic rate in mammals and a significant negative correlation between parasite diversity and host longevity. They hypothesized that parasites cause increased metabolic demands due to maintenance of the immune system.

The powerful selective force of parasites has also shaped human evolution, and the most famous pathogen for this (perhaps because it exerts the strongest pressure) is the malaria parasite, *Plasmodium* *falciparum*, and the maintenance of the sickle-cell gene. Although people homozygous for the allele suffer from a severe reduction in life expectancy (Platt et al. 1994), heterozygotes enjoy a resistance to malaria.

PARASITE-MEDIATED ECOSYSTEM SERVICES

Parasites and Health

In today's world, parasites are significant contributors to the global burden of human disease, have important demographic consequences, and can be obstacles to socioeconomic development (Sachs and Malaney 2002; Lopez et al. 2006). Parasite control and extirpation efforts have indeed increased health and well-being for millions. Yet might the loss of certain host–parasite interactions translate into impaired ecosystem services and diminished human well-being (Table 6.2)?

In developed regions, extreme reductions in the abundance of some parasites may contribute to a new suite of negative human health effects. Recent evidence suggests that contact with parasites (and non-pathogenic microorganisms) modulates the immune system's response to pathogens and allergens. Studies suggest that contact with saprophytic bacteria and parasitic helminths can reduce the risk of immune-mediated disorders such as inflammatory bowel disease and asthma (Falcone and Pritchard 2005; Rook 2009). This idea, termed the "hygiene hypothesis," might contribute to observed patterns of incidence of these disorders in developed countries. Consequently, there is currently empirical support and ongoing clinical trials for the therapeutic use of helminth infestations (Falcone and Pritchard 2005).

Certain parasites provide other kinds of direct benefits to humans. Leeches are used in reconstructive surgery and pain and wound management (Michalsen et al. 2003; Frodel et al. 2004). Parasites can also be potential sources of novel drugs and immune-modulating compounds (Fallon and Alcami 2006; McKay 2006). Parasite molecular processes are used in the research, development, and delivery of medically important molecules: using a virus to bind to specific receptors, therapeutic agents can be delivered to target tissues or organs (Douglas and Young 2006). Some parasites (predominantly intestinal helminths) bioaccumulate circulating heavy metals, which often concentrate in parasite tissue at levels orders of magnitude higher than in host tissue, potentially providing a direct service for hosts living in polluted environments (Sures 2003).

Finally, relatively little is known about the competitive interactions across the entire parasite community within a host individual. Loss of highly virulent

Table 6.2 Three Potential Prioritization Categories for Parasite Species Conservation

Risk-based	
	Affiliation with endangered, rare, or geographically restricted hosts
	Host specialists
	Transmitted inefficiently
	Complex transmission involving several hosts/vectors
Function-based	
	Species with higher link diversity in food webs
	Specialists of primary producers
	Ecosystem engineers
	Unique, non-redundant functions
	Causing significant morbidity/mortality in top-down controllers
Uniqueness-based	
	Phylogenetically unique
	Endemic

species from this community is clearly beneficial for the host. However, parasite diversity loss can also have negative ecological and epidemiological consequences for the host (Gompper and Williams 1998). For example, recent research shows that hosts infected with multiple strains of a pathogen may experience reduced mortality (Balmer et al. 2009), and that infection with vertically transmitted parasites can offer protection against viral infection (Hedges et al. 2008). Theoretically, the loss of specialist parasites could increase the risk of infection with generalist species, which often produce more severe morbidity (Dobson and Foufopoulos 2001; Dunn et al. 2009). While much more research is needed to understand the nature, strength, and local ecological context of these complex interactions, these examples suggest that blanket parasite eradication may lead to unintended costs for host populations.

Environmental and Biodiversity Indicators

Parasite species are also important indicators of environmental stress and can be incorporated into environmental monitoring programs (Marcogliese 2004; Sures 2004). The extent to which toxins accumulate in parasites at rates proportional to their environmental abundance determines the parasite function as an accumulation indicator. As environmental fluctuations in pollutant levels are more rapidly reflected in parasite tissue (Sures 2003), bioaccumulating parasites can be used as sentinels, capable of signaling health-threatening environmental conditions.

Parasites, particularly those with transmission cycles involving several species, can also function as biodiversity indicators. Parasites may be excellent indicators of food web structure and reflect the presence of diverse intermediate and definitive hosts in the ecosystem participating in parasite life cycles (Marcogliese 2004; Hechinger and Lafferty 2005; Lafferty et al. 2006). Hechinger and Lafferty (2005) found positive associations between bird diversity and abundance and trematode richness in their intermediate snail hosts. These trematodes can thus be used as useful biodiversity monitors providing information about bird communities through longer time periods and with a lower sampling effort than with host surveys (Hechinger and Lafferty 2005).

Information Sources

An increased understanding of parasite biodiversity offers us a range of new tools with which to understand the natural world. For example, the inclusion of parasites in food webs alters our understanding of the consequences of biodiversity loss. Traditionally, ecological models have suggested that the highest vulnerability to cascade effects is faced by those species occupying top trophic levels, while alternative models including parasites suggest that mid-trophic-level species are in fact most sensitive, because they are subject to both parasitism and predation (Lafferty et al. 2006). A range of examples of parasites as information models are found in the study of evolution, where the study of parasite diversity can aid in our understanding of host population dynamics, ontogeny, and phylogeny and strengthen hypotheses about niche specialization, adaptation, and speciation (Marcogliese 2005; Whiteman and Parker 2005).

PARASITE CONSERVATION

Threats to Parasite Persistence

The modern-day biodiversity crisis is most often portrayed in vertebrate terms, yet it is overwhelmingly a loss of invertebrate life, in which affiliate species such as parasites face the risk of co-extinction as their hosts decline (Dunn 2005; Dunn et al. 2009). Although the extensive diversity of this multiphyletic group means that generalizations about threat levels are difficult, parasites face synergistic threats to their persistence that are cause for conservation concern.

Medical and/or veterinary parasite interventions focused on active control and extirpation represent obvious direct threats to parasite survival. Parasite extirpation is a common goal in public health strategies and captive breeding and wildlife management programs. The subsequent attrition of non-target parasites can be expected to be high when and where control programs use broad-spectrum techniques. For example, broad-spectrum molluscicides are used in campaigns to control several parasites of public health and veterinary importance. However, snails are also hosts to a variety of other parasite species that become unintended and unseen targets of these strategies (Kristensen and Brown 1999; McClymont et al.

2005). Parasite eradication in *ex situ* situations represents a challenge for both the conservation status of the parasite and the evolutionary potential of the host (Gompper and Williams 1998). The deliberate removal or destruction of a given parasite species removes an entire lineage of co-evolutionary past and future co-evolutionary potential.

Beyond deliberate attempts to reduce parasite abundance, parasite conservation is intimately tied to host status. Factors threatening the host (e.g., habitat loss and fragmentation, overexploitation, emerging diseases, climate change, species invasions, and interactions among all of the above) imperil parasite persistence. This risk level increases with host specialization (Table 6.2). Compounding the issue, host populations must remain above parasite-specific thresholds of abundance to maintain viable parasite populations, which in fact might be greater than that required to cue conservation intervention (Altizer et al. 2007). Depending on the epidemiological factors that modulate this threshold (e.g., host specificity and transmission efficiency), it can be expected that parasite species will disappear long before their hosts do (Dunne and Williams 2009). These effects will be greater in multi-species transmission cycles as extinctions or significant decreases of just one link of the transmission chain can cause parasite extinction.

Only one parasite species is currently included in the 2009 IUCN Red List, the pygmy hog-sucking louse (*Haematopinus oliveri*), listed as critically endangered because of the rarity of its host, the pygmy hog (*Porcula salvania*) (IUCN 2009). Actual documented cases of parasite extinction are also scarce (see Koh et al. 2004 and Dunn et al. 2009). Estimates of parasite endangerment suggest that anywhere from around 2,000 (Table 6.3; Dobson et al. 2008) to over 5,700 (Poulin and Morand 2004) parasitic helminth species alone are likely be to threatened with extinction and at least 266 are already likely extinct (Table 6.3). The vast disconnect between one endangered host species and even the most conservative estimates of endangerment suggest that single-species listing efforts for

Table 6.3 Estimated Number of Vertebrate Host Species Endangered or Extinct Based on the 2009 IUCN Red List, and Corresponding Estimates of Parasitic Helminth Species at Risk of Vertebrate Definitive Host-Dependent Extinction or Definitive Host-Dependent Extinction

	Chondrichthyes	Osteichthyes	Amphibia	Reptilia	Aves	Mammalia	**Total**
Critically endangered and endangered hosts	67	535	1,238	243	554	637	3,274
Associated estimate of critically endangered and endangered parasitic helminths							
Trematoda	2	27	54	82	203	254	623
Cestoda	64	21	15	19	365	337	821
Acanthocephala	–	2	5	1	6	10	24
Nematoda	5	8	126	116	171	67	492
						Total	1,959
	Chondrichthyes	Osteichthyes	Amphibia	Reptilia	Aves	Mammalia	Total
Extinct and extinct in the wild	0	103	39	22	137	78	379
Associated estimate of extinct parasitic helminths							
Trematoda	0	5	2	7	50	31	96
Cestoda	0	7	1	5	60	25	97
Acanthocephala	–	1	0	0	1	1	3
Nematoda	0	3	5	30	28	5	71
						Total	266

Based on the methods and estimated vertebrate host and global parasitic helminth diversity data from Dobson et al (2008).

parasites are both a poor reflection of risk and unlikely to successfully chronicle their conservation plight (Dunn et al. 2009).

Present and Potential Approaches

Existing measures to conserve parasites are remarkably scarce. Academic calls for increased inclusion into endangered species listing (Dunn et al. 2009; Dunne and Williams 2009), pleas for attention to the high extinction risk associated with control interventions in *ex situ* conservation situations (Gompper and Williams 1998), and calls for inclusion in broader conservation strategies (Windsor 1995; Perez et al. 2006; Pizzi 2009) have grown louder in recent years. Yet practical solutions and explicit targets are rare. The intentional conservation management of host–parasite interactions within and outside protected area boundaries requires preserving a background level of transmission between host and parasite. In most cases, setting such transmission targets will be extremely complex.

In this section, we briefly discussed the extent to which parasites are currently incorporated in conservation approaches, and discussed ways to strengthen their representation, as well as potential challenges in this endeavor. As with all biodiversity targets, limited funding and resources need to be strategically allocated. Below we suggest a list of broad guidelines to highlight categories of parasite species that might require the most immediate attention from conservation managers. These include priorities based on extinction risk, key ecosystem roles, and functional or phylogenetic uniqueness (see Table 6.2). These general guidelines should be refined in the context of local conditions and updated with expanding information about the ecological relevance of parasite species.

SINGLE-SPECIES CONSERVATION

Single-species conservation measures, ranging from population assessments to species management or recovery plans, are often focused on concerns for species that are formally listed as threatened or endangered. This almost by definition implies they are in short supply for parasites. Poor representation on endangered species lists is a product of several factors. Survey efforts for invertebrate and microscopic taxa are often insufficiently replicated to complete dependable species lists for a given area (Samways and Grant 2007; Cotterill et al. 2008). A low and often geographically biased degree of taxonomic expertise may compound these limited survey efforts. If one adds to this the basic bioinformatics challenges faced by hyperdiverse groups (Clark and May 2002; Samways and Grant 2007), considerable ground must be made up before the distribution and therefore the extinction risk of parasites are properly assessed (Dunn 2005). Judging from the mismatch between conservation threat and the extent of inclusion in the IUCN Red List, parasites exemplify problematic single-species conservation targets. The benefits of listing a given species or group are readily apparent only when it has been adequately assessed (Regnier et al. 2009). This demands data that are unlikely to exist for parasites (Maudsley and Stork 1995). Creating high-quality population data for small-bodied, elusive, or cryptic taxa demands a costly and often difficult blend of geographic coverage, thorough host surveys, and molecular analyses. Yet without these data, the conservation potential of listing efforts and other conservation strategies is greatly diminished.

Save for one parasitic plant (Ecroyd 1995) we know of no published parasite recovery or management plan, even for those parasites that are obligates upon hosts whose long-term conservation is clearly challenged, such as geographically restricted or threatened host species (Durben and Keirans 1996) or those extinct in the wild (Gompper and Williams 1998). How might this situation change? We advocate that a minimal starting point is increased parasite surveys for host taxa currently globally assessed on the IUCN Red List. Parasite surveys could minimally be conducted for three easily targetable classes of hosts: those that are (1) geographically restricted, (2) endangered, or (3) in active decline. Their small or declining population sizes make them less likely to support the host–parasite interaction rates needed to sustain parasite persistence. These surveys can improve our understanding of the identity, degree of specialization, and threats faced by the subset of parasite species at a known high risk of co-extinction or co-decline.

In situ conservation planning and management for maintaining specific host–parasite interactions is related to those designed for their hosts: conservation targets and potential management actions should be identified, cost–benefit analyses carried out, feasible actions implemented, and effectiveness in reaching the goals continually monitored (Margules and Pressey 2000; Bottrill et al. 2008). Monitoring changes in a parasite spatial and host distribution, as well as changes in prevalence, is always necessary but especially important following environmental alteration or changes in the conservation management plans for ecosystems or host species (Lebarbenchon et al. 2006). *Ex situ* conservation strategies are also applicable for parasite biodiversity. In other cases, parasites of rare or threatened hosts could be isolated and maintained under controlled conditions in closely related abundant or non-threatened species until recovery efforts allow the original host populations to recover and the host–parasite interaction can be re-established in the wild (Gompper and Williams 1998).

CONSERVATION BY PROXY

Conservation by proxy or systems-level conservation refers to decision-making for entire ecosystems or landscapes, and includes a variety of interventions, from large-scale conservation planning to natural resource management. Conservation by proxy is in practice the most common type of conservation strategy for parasites, as conservation plans for hosts are considered umbrellas for parasites and other associates, typically without clear objectives, monitoring, or evaluation for these dependent taxa. However, to assume that host conservation will directly result in parasite conservation is dangerously complacent. Due to their threshold requirements for host population size, this assumption breaks down for small, captive, or fragmented populations of any of the species involved in a parasite transmission cycle (host, vector, or reservoir). Therefore, maintenance of the parasite fundamental niche requires a complex, systems-level view of conservation. For these reasons, parasite conservation requires its own assessments, targets, and monitoring.

The kinds of ecological changes that accompany host conservation strategies (e.g., protected-area design and management) affect parasite diversity and infection patterns (Ezenwa 2003; Lebarbenchon et al. 2006). *In situ* and *ex situ* health programs, food supplementation, vaccination, and translocations will also have effects on infection prevalence and incidence. This highlights the obvious fact that changes in host ecology will affect the ecology of its parasites, and that the net result can be detrimental for the host–parasite interaction, even if beneficial for the host in the short term. While we know of no clear conservation-by-proxy endeavor purposefully targeting the conservation of a parasite–host interactions, we suggest that the combination of comprehensive parasite surveys and long-term adaptive monitoring should be added to host conservation strategies whenever possible (Lindenmayer and Likens 2009). Important increases in our understanding of parasite species identity, the size and variation of effective parasite populations at the individual and population levels, and geographic variation among allopatric host populations are prerequisites to successful conservation management.

Finally, recent research showing that parasite ecology reflects the ecology of vertebrate hosts (Hechinger and Lafferty 2005; Hechinger et al. 2008) suggests that the current hosts-as-umbrellas-for-parasites approach might deserve to be turned around: maintaining endemic parasite transmission can, in some cases, provide a conservation target that, when met, will signify that other biodiversity components of an ecosystem remain viable. In these cases, rather than being an additional monitoring task, parasite biodiversity can be an inclusive conservation target, and parasite ecology an effective indicator of overall ecosystem health.

Conservation by Inspiration

Conservation-by-inspiration approaches rely upon capturing the attention and imagination of the public, funding bodies, and decision-makers to inspire investment in the protection of a particular species group or ecosystem. These approaches aim directly at highlighting the intrinsic or aesthetic value of single species, and espousing the utilitarian value of multiple species assemblages at larger spatial scales. Both approaches serve to motivate engagement with a given conservation issue yet focus on different biological targets (Caro and O'Doherty 1999; Lindenmayer et al. 2007).

Popular science books and newspaper articles that emphasize the positive roles of parasites in ecosystems and dangers of parasite biodiversity loss are a recent and welcome contrast to the usual publications unlikely to improve public perception of parasites (LaFee 2006; Zuk 2007). The scarcity of pro-parasite messages extends to the scientific literature: from journal inception through 2009, a single published article with "ecosystem services" in the title from the journals *Conservation Biology*, *Biological Conservation*, and *Biodiversity and Conservation* makes any reference to parasite biodiversity in the abstract. Within the textbooks that serve as the academic foundation in conservation biology education, cogent arguments of parasites as organisms deserving conservation attention are a rarity (Moritz and Kikkawa 1994; Groom et al. 2006; Riordan et al. 2007). In a survey of 76 English-language conservation biology textbooks published between 1970 and 2008, 69% either do not mention the terms "parasite" or "pathogens" in the index, or limit their discussions to descriptions of parasites as a threat to species of conservation interest (Nichols and Gómez 2011). This lack of inclusion in basic conservation education helps perpetuate the scarcity of knowledge about the practice of parasite conservation.

Overall, parasite species (as much of free-living biodiversity) still fail to capture the public's attention. The academic consilience among the fields of ecology, conservation, and epidemiology embodied by conservation medicine can offer knowledge and tools to discover and effectively communicate the roles of parasites as dominant, important, and vital members of every ecological system on Earth. Bridging this gap within the scientific community is still necessary, and a fundamental reframing of epidemiological issues in an ecological context may help demystify the study and conservation of parasites. Further engagement from conservation biologists and conservation medicine practitioners is needed to temper messages focused solely on disease causation with mentions of positive attributes of parasite biodiversity.

CHALLENGES AND CONFLICTS

Human aversion to most invertebrates is well documented (Kellert 1993). These aversions extend to microorganisms and are compounded through the funding, training, and academic networks that support conservation research and practice (Clark and May 2002; Samways 2005). The active inclusion of parasites in conservation strategies may open a Pandora's box of financial constraints, basic scientific hurdles, and public relations concerns. Anticipating and navigating these challenges will be critical to the future of parasite biodiversity and to the practice of conservation medicine.

Recent focus on emerging diseases may create a public relations issue for proponents of parasite conservation (Daszak and Cunningham 2002). Recent studies have shown that wildlife species are the most common reservoir of human emerging infectious diseases, and that emergence events have increased through time (Jones et al. 2008). For the lay public, it is hard to escape news reports concerning the H1N1 influenza pandemic, West Nile virus fever, or Ebola virus outbreaks. Conserving parasite biodiversity ultimately conserves the pool of pathogens that may spill over to populations of humans, domestic animals, and crops. This is a difficult idea to sell to donors and stakeholders, let alone impose upon local communities. Conceptually, however, this situation is similar to human–wildlife conflict, and much can be learned from the large body of literature dealing with strategies to prevent and mitigate it (e.g., buffer zones).

Another challenge for conserving parasites is simply the global lack of taxonomic expertise for most of the relevant groups (Brooks and Hoberg 2000). Given current funding opportunities and the enormous estimates of parasite biodiversity, there are simply too few researchers who can describe new taxa within the timeframe that is needed to know what species are out there, let alone identify those in need of conservation. As an example, Hugot et al. (2001) estimate that at the current rate of taxonomic effort, an additional 1,300 years of study will be necessary to produce a detailed record of nematode diversity.

Conflicts can also arise within the conservation community. Since parasites are still often overlooked by ecologists and conservation biologists, there may be conflicts related to allocating limited resources toward the conservation of parasites and away from other more conventional targets. Successful parasite conservation might also pose significant challenges for managers. Similar to poorly targeted top predator conservation measures, inappropriately estimated population targets for parasites may have strong, cascading effects on their host organisms. Managers of parasite biodiversity would be required to maintain an often-delicate balance between endemic and epidemic levels of transmission, and errors on either side could threaten either parasite or host. Further, given the potentially insurmountable public relations challenges of parasite-oriented conservation (e.g., a park for parasites), managers might need to set parasite conservation targets and strategies that are nested within those for other species.

Increasing the awareness of parasites as intrinsically valuable and critical elements in functioning ecosystems would seem an unchallenged good. However, calls for parasite conservation may create further concerns for conservation biologists and advocates to resolve: issue fatigue and negative public perception. We define conservation "issue fatigue" as disengagement from a conservation issue on the basis of the perception that effective action has not occurred or cannot occur; therefore, the issue in question deserves reduced attention or funding. When coupled with the daily stream of environmental admonitions, it is possible that the audiences reached by environmental advocacy may meet persistent calls for parasite awareness, consideration, and inclusion with a sense of weariness.

Beyond fatigue, the full implications of parasite conservation may be challenging for many to understand and accept. Advocating parasite conservation implies supporting death and sickness in wild species. While parasitism is as much a natural process as photosynthesis or predation, public perceptions are generally biased against the effects of parasites on their hosts (Daszak and Cunningham 2002). Suggesting that people accept various degrees of morbidity and mortality can be difficult and might be heard by some ears as a challenge to the credibility of conservationists. Conservation medicine is largely predicated on influencing human attitudes, knowledge, and behaviors. Promoting change in these values may be critical to gaining public acceptance of the full implications of maintaining ecosystem health.

CONCLUSIONS

Inclusion of parasite biodiversity in ecological thinking has highlighted its numerical and functional importance in ecosystems and through evolutionary time. Practitioners of conservation medicine are ideally poised to tackle the dual demands of predicting, preventing, and controlling the negative consequences of infectious diseases on all species on the one hand, while on the other preserving the contributions of parasites to healthy ecosystems. Further research is needed to guide the development of strategies to sustain parasite diversity. Some of this research will fall within discrete disciplinary lines: parasite surveys, descriptions, and taxonomic work within and across ecosystems are still a dire necessity. However, the transdisciplinary research and training promoted by conservation medicine is a critical tool with which to analyze complex ecosystem health issues such as parasite conservation. Beyond research, parasite conservation requires effective communication with a variety of audiences, emphasizing parasites and disease as natural components of the web of life.

Incorporating parasite biodiversity conservation into the science and practice of conservation medicine does not mean that all parasite species, at all times and in all ecosystems, deserve conservation efforts. It does, however, imply that there are important tradeoffs in conserving individual, population, and ecosystem health; that preserving healthy ecosystems requires maintaining infection; and that the costs and benefits of control and eradication strategies need to be considered in a systematic and inclusive manner. Parasite control, extirpation, and eradication will still be desirable outcomes. We only ask that these tradeoffs are considered and that parasite conservation (or elimination) is given appropriate weight in conservation decision-making and in the practice of ecological health.

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