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(Review Article)

Parasites as integrators of ecosystem health: A multi-taxable perspective on wildlife ecology

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Abstract

Parasites are increasingly recognized as critical components of ecological systems, with profound impacts on biodiversity, food web dynamics, and ecosystem functioning. Far from being mere agents of disease, parasites can serve as sensitive and integrative indicators of environmental health, responding predictably to changes in habitat quality, climate variability, pollution, and host biodiversity. This review synthesizes current knowledge on the ecological roles of parasites and their utility as bioindicators across multiple taxa, including mammals, birds, amphibians, reptiles, fish, and invertebrates. Emphasis is placed on how parasite diversity, prevalence, and community structure reflect underlying ecosystem processes and disturbances. Methodological approaches to parasite monitoring, including field sampling, molecular techniques, and host-parasite network analysis, are discussed alongside challenges such as complex life cycles and host specificity. Emerging research directions highlight the potential for integrating parasite-based metrics into conservation biology, ecosystem management, and biodiversity assessment frameworks. Recognizing parasites as integral ecological players offers a more comprehensive and realistic understanding of ecosystem health in a rapidly changing world.

Keywords: Conservation Ecology; Bioindicators; Parasite Biodiversity; Ecosystem Health; Host-Parasite Interactions

1. Introduction

Monitoring ecosystem health is fundamental to understanding biodiversity dynamics, detecting early signs of environmental degradation, and guiding effective conservation strategies [1,2]. Traditionally, ecological assessments have focused on conspicuous taxa such as birds, mammals, and plants, with parasites largely overlooked or regarded merely as agents of pathology [3]. However, growing evidence reveals that parasites are not peripheral but integral to ecosystem functioning, influencing host population dynamics, food web complexity, nutrient cycling, and evolutionary processes [4–6].

Parasites exhibit high sensitivity to environmental changes, including habitat loss, climate fluctuations, pollution, and shifts in host community composition [7,8]. Their life cycles often require multiple hosts or environmental stages, making them particularly vulnerable to ecosystem disturbances that disrupt critical linkages [9]. As such, parasite communities can act as early-warning systems, integrating biotic and abiotic changes over time and across trophic levels [10].

Recent studies have demonstrated that parasite diversity and community structure mirror patterns of biodiversity loss, habitat fragmentation, and ecosystem instability [11–13]. For example, reductions in parasite richness are associated with declining host diversity in degraded habitats [14], while changes in parasite prevalence and transmission dynamics can signal altered food web interactions or environmental stressors [15]. In aquatic ecosystems, parasite assemblages

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have been used to assess water quality and pollution gradients, while in terrestrial systems, shifts in parasite communities have revealed fragmentation and climate-induced range shifts in host populations [16–18].

Despite their potential, the use of parasites as bioindicators remains underutilized compared to more traditional taxa. Challenges such as complex life cycles, taxonomic uncertainty, and detection difficulties have historically limited their application in routine monitoring programs [19,20]. However, advances in molecular ecology, including environmental DNA (eDNA) and metabarcoding approaches, are now overcoming many of these barriers, enabling more comprehensive and non-invasive parasite community assessments [21,22].

This review aims to provide a multi-taxonomic perspective on the role of parasites as integrators of ecosystem health. It synthesizes current understanding of parasite ecological functions, explores case studies across diverse host groups, reviews methodological advances in parasite monitoring, and highlights challenges and future opportunities. Recognizing the value of parasites in ecological assessment frameworks promises to enhance biodiversity monitoring, ecosystem management, and conservation efforts in an era of unprecedented global environmental change.

2. The Ecological Roles of Parasites

Parasites are deeply embedded in the fabric of ecosystems, influencing a wide range of ecological processes. Their roles extend beyond parasitism to shaping biodiversity patterns, regulating host populations, modulating food webs, and contributing to ecosystem stability and resilience [23,24].

2.1. Parasite Biodiversity and Ecosystem Functioning

Parasites represent a significant proportion of global biodiversity, often exceeding the diversity of free-living species in many ecosystems [25]. Studies estimate that parasitic species may comprise over 40% of all known species, yet their ecological functions have traditionally been underappreciated[26]. By infecting a range of hosts across trophic levels, parasites contribute to energy flow and nutrient cycling within ecosystems [27]. For example, parasitic infections can alter host foraging behavior, metabolism, and movement patterns, indirectly affecting vegetation structure and predator-prey dynamics [28].

Furthermore, parasites promote biodiversity through mechanisms such as density-dependent regulation and competitive release [29]. By suppressing dominant species, they enable coexistence among multiple host species, maintaining community structure and functional diversity [30].

2.2. Parasite-Host Dynamics and Food Web Interactions

Parasites are intricately woven into food webs, occupying roles as consumers, prey, and even ecosystem engineers [31].

Host-parasite interactions often have cascading effects across ecosystems, influencing species abundance, behavior, and community assembly [32].

Complex life cycles that involve multiple hosts (e.g., trematodes, cestodes) connect distinct trophic levels, linking invertebrates, fish, birds, and mammals into intricate ecological networks [33].

Recent studies incorporating parasites into food web models have revealed that parasites increase connectance, interaction diversity, and network stability [34]. Ignoring parasites can lead to underestimation of the complexity and resilience of ecological communities [35].

Additionally, parasites may mediate trophic interactions by weakening prey species, thus affecting predator-prey dynamics and facilitating trophic cascades [36]. Such processes highlight the central role of parasites in maintaining ecosystem balance.

2.3. Parasites as Regulators of Host Populations

Parasites act as natural regulators of host population dynamics by influencing host survival, reproduction, and dispersal [37]. Chronic infections can reduce host fitness, leading to lower fecundity, impaired competitive ability, and increased susceptibility to predation [38]. In some cases, parasites have been implicated in host population cycles, such as those observed in cyclic rodent populations [39].

Density-dependent parasite transmission can impose regulatory feedback loops on host populations, preventing outbreaks and maintaining demographic stability [40]. For instance, parasitic nematodes have been shown to modulate the dynamics of wild ungulate populations in the Serengeti ecosystem [41]. Such regulatory roles underscore the importance of parasites as integral components of natural ecosystems rather than merely as pathogens to be eradicated [42].

3. Parasites as Indicators of Ecosystem Health

Parasites offer a powerful yet underutilized lens through which to assess ecosystem integrity. Due to their sensitivity to environmental perturbations, dependency on multiple trophic levels, and close association with host biodiversity, parasites can serve as reliable indicators of habitat quality, biodiversity loss, food web alterations, and ecosystem disturbances [43–45].

3.1. Sensitivity to Environmental Changes

Parasites are highly responsive to environmental factors such as pollution, habitat fragmentation, climate change, and land use modification [46]. For instance, the decline of parasite diversity in freshwater fishes has been strongly correlated with chemical pollution and eutrophication [47].

Similarly, habitat fragmentation can disrupt complex parasite life cycles by reducing host availability or altering host community composition, leading to declines in parasite richness and abundance [48].

Climate change can also affect parasite transmission dynamics by altering the distribution of hosts, vectors, and environmental stages [49]. Shifts in temperature and precipitation patterns have modified parasite life cycles in amphibians and led to novel disease outbreaks in wildlife populations [50]. Because parasites often require specific environmental conditions and host communities to complete their life cycles, changes in parasite assemblages can reveal subtle, cumulative ecosystem alterations before they are apparent through traditional monitoring of free-living species [51].

3.2. Indicators of Biodiversity Loss

Parasite diversity is often positively correlated with host diversity, making parasites indirect indicators of broader biodiversity patterns [52].

Loss of host species through habitat destruction or hunting can lead to secondary extinctions of associated parasites, a phenomenon known as "coextinction" [53].

In some cases, parasites themselves can be used to predict the richness and health of host communities. For example, declines in gastrointestinal helminth diversity in mammals have been linked to ecosystem degradation and defaunation [54].

Moreover, generalist parasites may dominate in disturbed ecosystems, while specialist parasites sensitive to host community structure decline, signaling a loss of ecological complexity [55].

Thus, monitoring parasite diversity and community composition provides valuable insights into the status of host assemblages and overall ecosystem biodiversity [56].

3.3. Indicators of Trophic Interactions and Stability

Parasites occupy key positions in food webs, often linking multiple hosts across trophic levels [57]. Disruptions in food web structure, such as the loss of predators or herbivores, can affect parasite transmission routes, prevalence, and diversity [58].

Stable and intact ecosystems tend to support more complex and stable parasite-host networks [59]. Conversely, simplification of food webs through species extinctions or functional homogenization often results in reduced parasite diversity and altered infection dynamics [60].

Network-based analyses of host-parasite interactions have revealed that parasites enhance food web connectance, modularity, and robustness [61]. Declines in parasite complexity may therefore signal weakened trophic interactions and reduced ecosystem resilience [62].

Parasites thus provide a multidimensional reflection of ecological processes, offering insights into food web integrity, energy flow, and community stability that might otherwise remain hidden [63].

4. Case Studies Across Taxa

Case studies across diverse wildlife groups demonstrate the effectiveness of parasites as integrators of ecosystem health. Parasite communities in mammals, birds, amphibians, fish, and invertebrates reflect a wide range of environmental gradients and anthropogenic pressures [64].

4.1. Mammals

In mammalian hosts, parasite diversity and prevalence have been linked to habitat fragmentation, urbanization, and biodiversity loss [65].

For example, studies on rodents in fragmented landscapes show a decline in specialist parasites and a rise in generalist parasites as habitat quality deteriorates [66].

Similarly, carnivores living in disturbed habitats often exhibit altered parasite communities, reflecting trophic shifts and prey base changes [67].

In African ecosystems, lion (*Panthera leo*) populations in protected areas harbor more diverse parasite assemblages compared to populations outside reserves, indicating a correlation between parasite diversity and ecosystem integrity [68].
Changes in parasite loads in wild ungulates such as wildebeest (*Connochaetes taurinus*) have also been used to assess grazing pressure and water availability in savanna ecosystems [69].

4.2. Birds

Avian parasites, including blood parasites like *Plasmodium*, *Haemoproteus*, and *Leucocytozoon*, are sensitive indicators of habitat quality, climate variability, and fragmentation [70].

Elevated prevalence of avian malaria in Hawaiian forest birds has been strongly linked to changes in temperature and mosquito vector dynamics driven by climate warming [71].

In Neotropical forests, declines in blood parasite diversity have paralleled declines in bird community diversity, reflecting both direct and indirect impacts of deforestation [72].

Moreover, parasite-mediated changes in bird physiology and behavior (e.g., altered singing rates, reduced reproductive success) offer additional indicators of ecosystem stress [73].

4.3. Amphibians and Reptiles

Amphibians, often considered sensitive bioindicators themselves, also harbor parasite assemblages that reflect environmental conditions [74].

Increased trematode infections in amphibian larvae have been associated with eutrophication and habitat degradation, providing a link between pollution and parasite-mediated disease emergence [75]. Chytridiomycosis, caused by *Batrachochytrium dendrobatidis*, exemplifies how emerging parasitic pathogens can act as sentinels of environmental change and species declines in amphibians globally [76].

In reptiles, helminth community composition in lizards has been used to assess habitat disturbance, with degraded habitats often harboring fewer parasite species but higher prevalence of opportunistic taxa [77].

4.4. Fish and Aquatic Systems

Fish parasite communities offer some of the clearest examples of using parasites as ecosystem health indicators [78]. Eutrophication, chemical contamination, and habitat simplification in aquatic environments often lead to reduced parasite diversity and altered transmission dynamics [79].

For example, parasite richness in fish has been shown to decline along pollution gradients in rivers and estuaries [80]. Certain parasite taxa, such as monogeneans and trematodes, are highly sensitive to water quality and can serve as biological monitoring tools complementary to traditional measures like macroinvertebrate indices [81].

4.5. Invertebrates

Parasites of invertebrates, although less frequently studied, also provide valuable insights into ecosystem processes [82]. Microsporidians, nematodes, and parasitoid wasps that infect insect hosts respond predictably to habitat fragmentation, pollution, and pesticide exposure [83].

Declines in parasitoid diversity and abundance have been linked to agricultural intensification and landscape homogenization, highlighting the cascading effects of ecosystem simplification on multitrophic interactions [84]. Furthermore, parasitic infections in pollinators such as bees have been associated with changes in floral diversity and pesticide exposure, linking parasite dynamics to ecosystem service provision [85].

5. Methodological Approaches in Parasite Monitoring

Effective monitoring of parasite communities requires diverse methodological approaches tailored to the ecology of parasites and their hosts. Recent advances in molecular ecology and network analysis have enhanced the ability to detect, identify, and interpret parasite data in the context of ecosystem health [86].

5.1. Field Sampling and Host Examination

Traditional field-based parasite monitoring relies on direct examination of hosts through necropsy, fecal analysis, blood smears, or external inspection [87].

Necropsy provides comprehensive data on endoparasite burdens but is invasive and often limited to dead or sacrificed individuals [88].

Non-invasive methods, such as fecal flotation, PCR-based detection from feces, and blood smears for hemoparasites, allow sampling without lethal collection, facilitating longitudinal monitoring in wild populations [89].

Standardized sampling protocols, including consistent effort across sites, appropriate host stratification (e.g., by age, sex), and rigorous preservation methods, are critical for reliable parasite community assessments [90]. However, traditional sampling can miss cryptic or low-intensity infections, emphasizing the need for complementary molecular approaches [91].

5.2. Molecular Methods (eDNA, Metabarcoding)

Molecular techniques have revolutionized parasite ecology, enabling sensitive, non-invasive detection of a broad range of parasite taxa [92]. Polymerase chain reaction (PCR), quantitative PCR (qPCR), and next-generation sequencing (NGS) allow species-level identification from minimal sample material such as blood, feces, or environmental DNA (eDNA) from soil, water, or air [93].

Metabarcoding approaches targeting conserved genetic markers (e.g., 18S rRNA, ITS regions) enable simultaneous detection of multiple parasite species from environmental samples, providing a community-wide view of parasitic biodiversity [94].

eDNA techniques have been successfully applied to monitor helminths in aquatic ecosystems, protozoan parasites in wetlands, and blood parasites in bird populations without capturing or handling hosts [95]. Despite their advantages, molecular methods can be limited by incomplete reference databases, PCR biases, and difficulties in quantifying infection intensity [96].

5.3. Network Analysis of Host-Parasite Interactions

Host-parasite interactions can be represented as bipartite networks, allowing visualization and quantitative analysis of community structure, specialization, modularity, and robustness [97].

Network analysis offers insights into ecosystem complexity, trophic integration, and resilience by examining how parasites connect different host species and trophic levels [98].

Metrics such as connectance, nestedness, and modularity provide measures of network stability and vulnerability to disturbance [99].

Changes in network structure, such as reduced modularity or loss of specialist links, can signal ecosystem degradation or biodiversity loss [100]. Integrating network ecology into parasite monitoring frameworks enhances the ability to detect ecosystem-level changes beyond simple prevalence or diversity metrics [101].

6. Challenges and Limitations

While parasites offer promising opportunities as indicators of ecosystem health, several methodological, ecological, and conceptual challenges must be addressed to fully realize their potential [102].

6.1. Complexity of Parasite Life Cycles

Many parasites possess complex life cycles involving multiple intermediate and definitive hosts, with distinct ecological niches and trophic interactions [103].

Disruptions at any stage due to host population declines, habitat loss, or environmental changes can alter transmission dynamics or result in the loss of parasite species [104].

Such complexity makes it difficult to attribute observed changes in parasite communities to specific environmental drivers without detailed knowledge of host ecology and transmission pathways [105]. Moreover, parasites with direct life cycles may respond differently to environmental changes compared to those requiring multiple hosts, complicating interpretation [106].

6.2. Host Specificity and Detection Issues

Parasite species vary widely in their degree of host specificity. Some are highly specialized, infecting only a narrow range of hosts, while others are generalists exploiting multiple host species [107].

Loss of specialist parasites may go unnoticed if monitoring efforts are not sufficiently targeted or if host sampling is incomplete [108].

Accurate detection and identification of parasites, especially cryptic or low-prevalence species, remain technical challenges despite advances in molecular diagnostics [109].

False negatives due to low parasite loads, intermittent shedding, or suboptimal sample preservation can bias community-level inferences [110].

6.3. Ethical and Logistical Challenges

Traditional parasite sampling methods, such as necropsy, blood sampling, or invasive procedures, raise ethical concerns, especially for endangered or protected species [111].

Ethical review boards and animal welfare regulations increasingly require non-invasive or minimally invasive techniques, which may limit the scope of parasite surveys [112].

Logistical constraints, including limited access to remote or politically unstable regions, difficulties in maintaining cold chains for molecular samples, and shortage of parasitological expertise, further restrict large-scale or long-term monitoring efforts [113].

6.4. Interpretation Challenges in Changing Ecosystems

Parasite community dynamics reflect both environmental changes and intrinsic host factors, such as demography, immune status, and behavior [114]. Separating environmental signals from host-related variation requires careful study design, replication, and integration of host ecological data [115].

Additionally, anthropogenic factors such as introductions of invasive species, translocation of hosts, and emerging diseases can create novel host-parasite assemblages, complicating baseline comparisons [116]. In rapidly changing ecosystems, parasite responses may lag behind environmental degradation or exhibit non-linear or threshold effects, requiring long-term monitoring to detect meaningful trends [117].

7. Future Directions

Emerging technologies, theoretical advances, and integrative conservation strategies offer new opportunities to strengthen the role of parasites as indicators of ecosystem health. Several key directions can guide future research and applications [118].

7.1. Integration into Biodiversity Monitoring Programs

Parasites should be systematically included in biodiversity assessments and ecological monitoring frameworks alongside traditional taxa [119].

Long-term studies incorporating parasite metrics such as diversity, prevalence, and network structure can provide early-warning signals of ecosystem degradation that may be missed by surveys of free-living organisms alone [120].

Standardizing protocols for parasite sampling, identification, and reporting across different ecosystems will enhance the comparability and utility of parasite data in conservation planning [121].

7.2. Advances in Genomics and Environmental DNA (eDNA)

Continued development of genomic tools and environmental DNA (eDNA) methods will expand the scope, sensitivity, and scalability of parasite monitoring [122]. High-throughput sequencing, metagenomics, and transcriptomics offer unprecedented opportunities to characterize entire parasite communities from complex environmental samples [123].

Building comprehensive reference libraries of parasite genetic sequences, especially for underrepresented taxa, will improve taxonomic resolution and detection accuracy in metabarcoding studies [124]. eDNA-based surveillance could enable large-scale, non-invasive monitoring of parasite biodiversity across terrestrial, freshwater, and marine ecosystems [125].

7.3. Host-Parasite Network Ecology

Network approaches can be expanded to model host-parasite interactions under scenarios of habitat loss, climate change, species invasions, and conservation interventions [126].

Dynamic network models incorporating parasite transmission, host switching, and extinction risk can provide predictive frameworks for ecosystem responses to environmental change [127].

Integrating network properties such as modularity, nestedness, and robustness into conservation assessments may improve the identification of vulnerable systems and guide targeted management actions [128].

7.4. Parasites and Ecosystem Services

Research should increasingly explore the role of parasites in regulating ecosystem services, such as pest control, nutrient cycling, and food web stability [129]. Understanding the functional contributions of parasites can shift perceptions from seeing them solely as pathogens to recognizing their broader ecological value [130].

Quantifying how parasite-mediated processes contribute to ecosystem resilience may highlight their relevance in sustaining biodiversity and ecosystem functionality under global change pressures [131].

7.5. Cross-Taxon and Multitrophic Monitoring

Parasite monitoring should be integrated into multitrophic biodiversity surveys that include plants, free-living animals, microbes, and abiotic variables [132]. Such holistic approaches would reveal the interconnectedness of species and ecological processes, providing a more complete understanding of ecosystem health [133].

Cross-taxon monitoring programs that link parasite dynamics to host population trends, vegetation changes, and climate variables will enhance early detection of ecosystem stress and collapse risks [134].

8. Conclusion

Parasites are essential yet often overlooked components of biodiversity and ecosystem function. Their ecological roles as regulators of host populations, connectors of trophic networks, and drivers of evolutionary processes highlight their profound influence on ecosystem stability and resilience. Because of their sensitivity to environmental changes, dependence on host diversity, and complex life histories, parasites serve as powerful integrators of ecosystem health.

Across mammals, birds, amphibians, fish, and invertebrates, empirical evidence demonstrates that changes in parasite diversity, prevalence, and network structure provide early and sensitive indicators of habitat degradation, biodiversity loss, climate change, and ecosystem instability. Methodological advances, particularly in molecular ecology, environmental DNA (eDNA) detection, and network analysis, are rapidly expanding the potential to monitor parasite communities at broader spatial and temporal scales.

Nevertheless, challenges remain. The complexity of parasite life cycles, host specificity, ethical concerns in sampling, and the need for long-term, standardized monitoring frameworks must be carefully addressed. A nuanced understanding of parasite ecology combined with emerging technologies and integrative, multitrophic approaches will be crucial to fully incorporate parasites into conservation biology, ecological monitoring, and ecosystem management.

Recognizing parasites not merely as threats but as key indicators of ecosystem integrity broadens the scope of biodiversity science. In an era of unprecedented environmental change, embracing the ecological significance of parasites offers a richer, more realistic, and more effective framework for safeguarding the health of our planet’s ecosystems.

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