Conservation Biology

Diversity

Recognition of the discipline of conservation mycology

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Fungi constitute one of the major lineages of life (organisms treated as fungi are also scattered in other lineages). Kingdom Fungi are quite separate to Animalia and Plantae, but fungi are intimately connected to other biota through food webs and symbioses as decomposers, endophytes, pathogens, lichens, and mycorrhizas. During much of the 20th century, fungi were either ignored or perceived as intractable in conventional conservation initiatives. This oversight was especially due to the paucity of information on demography and ecology, lack of awareness of the magnitude of fungal diversity, difficulty of sampling for fungi, and complexity of species delimitation and identification. Culturally and politically, conserving overlooked organisms often viewed as pests challenged paradigms devised for orchids and elephants. Consequently, fungi were rarely considered in articles about conservation in journals such as *Conservation Biology* (Fazey et al. 2005).

Hawksworth (1991) published an influential review highlighting the scale of fungal biodiversity (then estimated at 1.5 million species) and touched on the "scant attention" paid to fungal conservation in most countries. Over the last several decades, conceptual and technological advances have overcome some traditional barriers to consideration of fungal conservation, and there is a growing literature explicitly dealing with fungi conservation (Moore et al. 2001; Heilmann-Clausen et al. 2014).

Recent innovations and initiatives in the way fungi are studied and regarded mean it is timely to recognize the discipline of conservation mycology within conservation science. Advances include acceptance of fungi as a major unit of biota, alongside flora and fauna (Pouliot & May 2010; Minter 2011); recognition that most fungal species formerly thought to occur across continents are complexes of species, each with distinct distributions and habitat requirements; quantum step-change in digitization rates of specimen and observation data in tandem with establishment of portals for data entry and access; recognition of the vital role of fungi in ecosystem functioning as symbionts (e.g., mammalian and arthropod mycophagists and ectomycorrhizal forest trees) and as recyclers; combined sampling and identification of fungi enabled via metabarcoding; increased citizen science engagement with fungi; and increased activity of organizations focused on fungal conservation at international to regional levels, which has led to increases in formal conservation assessments of fungi across multiple jurisdictions.

Heilmann-Clausen et al. (2014) promoted the integration of fungi into conservation science across 5 areas:

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Table 1. Key characteristics of fungi that create issues for their conservation.

Characteristic	*Issue*
Diversity	likely about 3 million species globally, but 10% currently named
Invisibility	propagules (spores) and feeding bodies (mycelia) and many sporing bodies microscopic; visible sporing bodies often ephemeral
Overlooked	largely absent from policy and management documents and interpretation media for natural areas
Reference collections	incomplete sampling of diversity; lack of comprehensive barcode library for interpreting environmental DNA and comprehensive fungal tree of life for evolutionary context
Scale	individuals and communities occur at a diversity of scales from tiny (e.g., inside insect guts or leaves) to landscape (individuals among the largest organisms on the planet)
Language	separate kingdom of the natural world, often lumped under plants or as microbes, which hides biological and functional uniqueness
Attitudes	often regarded as pests rather than integral components of ecosystems
Interconnectedness	most are symbionts; ecological studies often deal with fungi and their partners separately
Paradigms	single-species approach to conservation assessment (such as via red listing) beginning, but guild and whole-community approaches are also required
Communication	challenge of collating existing information about fungi conservation and transferring and translating this between researchers, land managers, and citizen scientists

fungi as habitats and providers for other organisms, indicators of ecosystem trends, indicators of habitats, links to human societies, and sources of novel tools and approaches. They called for conservation scientists to "appreciate the crucial role of fungi in nature" and "engage mycologists in their work." The next step is to bring conservation mycology to the fore. Fungi have unique phylogenetic, biological, and social characteristics and associated issues (Table 1) that make conservation mycology a necessary and constructive conceptualization.

Initially, impetus for conserving fungi came from scientists whose focus was taxonomy but who were aware of declines in and threats to fungi. Subsequently, efforts to conserve fungi increasingly had an ecological focus. Now, progress in fungal conservation requires a broad set of skills. We propose conservation mycology as a research discipline and practice drawing on taxonomy, ecology, biogeography, demography, and population genetics. Conservation mycology, as with conservation science in general, is multidisciplinary and encompasses anthropology, sociology, and political science.

Developing a research agenda that contributes to effective fungal conservation is a primary reason for elaborating the new discipline of conservation mycology. Suggested research questions (Table 2) are specific to fungi and of wider theoretical and practical relevance. Molecular techniques will assist greatly in tackling currently intractable aspects. A genealogical concordance approach to the rigorous recognition of phylogenetic species is increasingly applied to fungi, and barcoding is a practical tool for identification (Geml et al. 2014). Metabarcoding provides unprecedented characterization of the fungal community in any substrate (e.g., soil, insect guts, plant roots or leaves). Nevertheless, for rare species, presence of sporing bodies (such as mushrooms) remains the most practical tangible evidence that a species is established at a site.

Demography and population dynamics are areas of conservation mycology where research is keenly needed because of the importance of understanding population trends when carrying out conservation threat assessments. Naturally, the most detailed understanding of fungal populations to date comes from fungi of practical concern in medicine, agriculture, food production, and forestry. A key challenge for conservation mycology is to expand insights gained from model pathogens to fungi in natural ecosystems. There is little known about life-history features in natural populations of fungi, especially effectiveness of spore dispersal, significance of the spore bank, establishment of mycelia, and turnover and longevity of individuals. In fact, the diffuse and potentially fragmenting nature of the largely hidden feeding bodies of fungi challenges notions of individuals, as applied to macro-organisms, and requires appreciation of clonality in the definition and recognition of individuals. For macrofungi, there is now a pragmatic guide for estimation of key measures in the IUCN threat assessment process, such as the number of individuals, anchored in best available science (Dahlberg & Mueller 2011). Such guidelines need to be extended, based on in-depth studies of exemplar fungal species, across the diversity of trophic guilds, reproductive strategies, and lineages.

There is a strong connection between conservation mycology and citizen science initiatives in mapping and monitoring fungi (Irga et al. 2018). Much of the increasing knowledge of species distribution, host preference, and frequencies in different habitats comes from observations by amateurs, albeit focused on sporing bodies. Engagement of nonspecialists is being facilitated by mass data mobilization and visualization, particularly through portals such as MyCoPortal (mycoportal.org) and Atlas of Living Australia (www.ala.org.au). An important role for conservation mycology is supporting citizen scientists to collect data in a rigorous yet realistic manner. Already,

Table 2. Research agenda for conservation mycology.

How to use ecological knowledge for the 10% of fungi named to effectively conserve all fungi?
Are there effective surrogates for fungi in monitoring and reserve design (either other fungi or other biota)?
How does the grain and patchiness of fungal communities (at micro and landscape scales) affect efforts at conserving them via surrogates?
How to standardize monitoring of fungi for use in policy-mandated surveys such as environmental impact assessments?
How to best detect and monitor rare fungi (including absences) by integrating surveys of sporing bodies and metabarcoding?
What are effective management practices for fungi (e.g., in silviculture, or in relation to fire or grazing regimes) and how do these compare with existing practices developed for habitats, plants, or animals?
What are the pros and cons of different management settings that aim to integrate management of fungi with that of other biota, and when is it more appropriate to focus on fungi as a group, or individual species of fungi?
How do life history characteristics (population size, turnover, size of individuals, etc.) vary across fungal morphogroups, lineages, and guilds and how to measure these?
How to challenge and mitigate negative attitudes about fungi among the public, land managers, and policy developers?
How to engage foragers in conservation (collecting and eating fungi is major point of contact with fungi in many societies)?

data provided by citizen scientists are contributing to the development of management recommendations, such as for fungi expected to be affected by climate change (Mair et al. 2017).

A particularly significant milestone for fungal conservation has been the recent addition of the first 100 species of fungi to the IUCN Global Red List of Threatened Species (Mueller 2017). Nomination under threat-status legislation is now also possible in many jurisdictions nationally and regionally for fungus species and communities (assemblages). Comprehensive national conservation status assessments are available for the fungi of over 30 European countries and New Zealand, and conservation assessment of more than 10,000 species of fungi from China is underway. However, listing is but one step in effective conservation. Identifying the threats and ecological requirements of listed species and developing guidelines to mitigate these threats is essential.

Initial conservation efforts for fungi focused on individual, well-known species of larger fungi, such as mushrooms and lichens, and were facilitated by specific knowledge of their ecological requirements. The molecular approach that underpins species delimitation and characterization of individuals and populations for particular species of fungi can also be applied to characterization of the mycobiome. The magnitude of fungal biodiversity, in the order of millions of species globally (Hawksworth & Lücking 2017), demands a top-down (community) approach to conservation while augmenting the bottom-up (species) approach. Across the mycobiome, investigating relationships between the fungal community and the plant community is critical because the latter is what is most often actively managed.

The interconnectedness of fungi with other biota provides opportunities to extend the single-species approach. Fungal hyphae are microscopic, often unseen unless producing reproductive structures, yet they pervade soils and the interior and exterior of plants and arthropods across the globe. There is now increased awareness of the importance of the holobiont (fungus + host) to understanding organisms and ecosystems (Vandenkoornhuyse et al. 2015). This perspective can usefully extend to conservation, where protection of individual biotrophic fungi (whether mutualists, such as mycorrhizas, or pathogens) is intimately bound up with protection of their biotrophic partners (the converse also applies).

Ecosystem-management practices developed for other organisms may not be optimal for fungi, for example, those related to fire or grazing regimes. Management agencies will need to draw on the skills and knowledge of conservation mycologists to integrate the management of fungi into existing practices. In situ conservation has been implemented for some fungi. However, well-established, practical concepts in conservation science underpinned by research (e.g., ex situ conservation, reintroduction, and restoration) are only beginning to be applied to fungi. It will be essential to foster a 2-way flow of information between conservation mycology researchers and practitioners so that practical questions are addressed and results of research are integrated into practice.

Social-political progress around concepts of fungi and understanding of their diversity and ecological importance needs to continue. Developing clarity in language (fungi are neither plants nor all microbes, despite often being described as such) and improving legislative coverage should be focus areas. There is tension between integration and separation, but the interconnection of fungi with other life is a useful metaphor for signposting promising approaches. An obvious example would be the enrichment of seed banks to become seed and spore banks, which would lead to better conservation outcomes for both fungi and plants, the majority of which are obligately mycorrhizal.

A conservation mycology approach will contribute to effective conservation of not only fungi but also biotic interconnections and consequently all life. The research agenda for conservation mycology has potential to inform practical efforts to conserve fungi and addresses fundamental issues of ecology, including providing explanations for the extraordinary diversity of fungi at all scales. We encourage the use of *conservation mycol-*

ogy as a keyword for publications and in meetings and conferences, and recommend the creation of positions for designated conservation mycologists, particularly in conservation and management agencies. We invite mycologists to address research questions fundamental to conservation mycology and conservation scientists to be prepared to connect with fungi to the benefit of their science and fungi.

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