The mycological social network: a way forward for conservation of fungal biodiversity

Peter J Irga[1*], Laura Dominici[2], Fraser R Torpy[3]

1. Plants and Environmental Quality Research Group, University of Technology Sydney, School of Civil and Environmental Engineering, Faculty of Engineering and Information Technologies.

2. Applied Ecology Research Group, Politecnico di Torino, DIATI - Department of Environment, Land and Infrastructure Engineering

3. Plants and Environmental Quality Research Group, University of Technology Sydney, School of Life Sciences, Faculty of Science

*Corresponding email address peter.irga@uts.edu.au

Summary

Because knowledge of fungal diversity is very incomplete, it is possible that anthropogenic impacts are driving species to extinction before they have been discovered. Fungal inventories are still incomplete and do not reflect the complete diversity of this large taxon. Whilst molecular advancements are leading to an increased rate of species discovery, there is still much to be done to understand the diversity of fungi, identify rare species and establish conservation goals. Citizen science via social media could play an increasingly important role in mycological research, and its continued development should be supported and encouraged. The involvement of non-professionals in data collection helps increase public awareness, as well as extending the scope and efficiency of fungal surveys. Future academic mycological research could benefit from social media interaction and engagement with the amateur mycological community, and may accelerate the achievement of more effective conservation goals.

Keywords: Biodiversity conservation; diversity; mycology; amateur; citizen science; social media

Introduction

Debates as to the need for the conservation of fungi have been prompted by threats to biodiversity throughout the world. Fungi are highly diverse and essential components of all ecosystems as symbiotic partners, predators and parasites, decomposers and nutrient cyclers, and sources of food for vertebrates and invertebrates (McMullan-Fisher et al. 2011). While the broad ecological importance of fungi justifies consideration of their conservation, discourse regarding biodiversity conservation has seemingly excluded fungi, with any consideration usually limited to the possible threats they pose to agriculture, food security and the conservation of other species (Field et al. 2020). Reasons proposed for this treatment pertain to the large and generally under-described diversity of the fungi, and a general indifference to their conservation (Grube et al. 2017): with conservation decisions at the species level driven more by the popularity and perceived 'charm' of an organism rather than from the rationale of their significance to the greater ecosystem. Additionally, the omission of fungi in conservation efforts has been attributed to the lack of relationship that humans have with the organisms, especially when compared to the biophilia displayed by humans with animals and plants (Moore et al. 2008). Furthermore, fungal species are responsible for spoilage of food, deterioration of building materials, and some represent threats to human health through their pathogenic and toxigenic activities (Arora & Shepard, 2008), potentially hindering conservation efforts through 'mycophobia' (Peintner et al. 2013).

Fungal diseases have caused some of the most severe extinctions ever witnessed in wild species, and are jeopardizing food security (Fisher et al. 2012). For example, high-profile declines in wildlife have been caused by Geomyces destructans (Boyles et al. 2011, Frick et al. 2010), increasing the probability of extinction for many species of North American bats. Additionally, the skin-infecting amphibian pathogen, Batrachochytrium dendrobatidis, is implicated in the greatest disease-driven loss of biodiversity ever documented, causing infections to over 500 species of amphibians in 54 countries (Byrne et al. 2016). Taken together, these recent events have exacerbated the rationale of fungi representing a threat to the biota, rather than as a target for conservation efforts.

This review aims to describe the attention given to fungi in biodiversity conservation policy documents, management plans and formal conservation schedules throughout the world, describe the methods used to determine the diversity of fungi, detail the general lack of awareness of mycological species in the scientific community, and quantify the scarcity of mycology-associated curricula and the lack of mycologists in research institutions. This review then outlines a potential remediating strategy, by quantifying the growing community interest, and citizen science initiatives through social media or otherwise that contribute to the concept of community-based learning and could significantly contribute to mycology.

Conservation Mycology

The 1992 Rio Convention on Biological Diversity (CBD) played a significant role of driving dialogue in regards to the conservation of biological diversity, initiating discourse at a global political level (Panjabi 1993). This conservation initiative was presented in terms of 'animals, plants and microorganisms', with all microorganisms combined into an arbitrary third group based solely on organism size (Dahlberg and Mueller 2011). Several aspects of fungal biology and ecology lead to this group not fitting well into this grouping, and their consideration in global conservation planning has consequently largely been forsaken (Suryanarayanan et al. 2015). The 'right' of fungi for their conservation has been established, but the convention has provided no policy or framework to enable it.

Nevertheless, as information on fungal ecology expands, including detailed descriptions of population dynamics, their roles in ecosystem functioning, especially in relation to symbioses, interest in the ecological significance, if not the conservation of fungi, is growing. Although in a fledgling state, a community of fungal conservation advocates has emerged in recent decades (Davoodian 2015). These interested parties are promoting critical intellectual discourse on the matter, either though organizing conferences, or promoting the idea of incorporating fungi into conservation planning (Barron 2011). Though much of the groundwork remains to be conducted, these pioneering efforts are major steps towards a more comprehensive outline for fungal conservation and thus biodiversity and ecosystem conservation (Barron 2011). On a regional scale, national Red Lists started to emerge in the 1980s, first being promoted in Germany in 1982. Currently, more than 35 countries have some form of Red List that includes fungi (Sadiković & Kuštera 2013). Further, these efforts may have fostered a baseline worldwide interest in the conservation of fungi, evidenced by the many fungal conservation groups established in the past decades, such as the European Council for the Conservation of Fungi, the International Society for Fungal Conservation, and the International Union for Conservation of Nature's (IUCN) Fungal Committee.

In addition to the growing efforts in conservation governance, the importance of fungi to symbioses with plants has been recognized, and thus included in The Global Strategy for Plant Conservation (GSPC), which is a strategy, established and implemented by The Convention on Biological Diversity (CBD) in 2002 (Jackson & Kennedy 2009). The GSPC provided an important new opportunity to focus on the potential loss of tens of thousands of threatened plant species, with those working within its framework deemed fundamental to delivering the GSPC and advancing the conservation of both plants and fungi (Le Breton et al. 2019). Further, in 2018, Kew Royal Botanical Gardens supported by the Sfumato Foundation released a benchmark publication (Willis 2018). It was comprehensive, describing all the positive interactions fungi provide, to fungal threats to ecosystems and fungal responses to climate change. More importantly, it detailed the collation of 2,189 new species of fungi described during 2017 alone, and described the challenges of fungal conservation, stating the taxonomic imbalance within the field of biological conservation. The continued activity and expansion of such groups illustrates the increasing understanding of the importance of fungi across stakeholders from academic, political, and public spheres.

The collection and collation of species conservation data utilize three main tools (Dahlberg et al. 2010): inventories, mapping and Red Lists. The lack of scientific data available on rare fungi, and thus their potential to become endangered, has largely led to their comparatively recent inclusion on IUCN Red Lists. Additionally, an obvious weakness with the fungal Red Lists provided so far is their national scope, making comparisons across larger regions challenging (Halme et al. 2017). To overcome this, Ódor et al (2006) proposed a list of 'fungi of special interest' on the scale of continental Europe to facilitate discussion on how the fungi indigenous to beech forests were affected by forest management and fragmentation across countries from Denmark to Slovenia, and to identify regions with the highest conservation value. This list has not been completed as of the time of writing, nor has it entered the planning stages in other countries that have equivalent, if not greater, fungal biodiversity, such as Australia. There has been some progress; in 2019 there were finally more than 340 species included in the IUCN Red List, however, still very incomplete. In light of this, it was proposed that three alternative conservation strategies could be adopted to protect fungal biodiversity (Allen & Lendemer 2015). The first strategy is to wait for ecological literature and taxonomic data to become available, after which time the conservation of fungal species could take place using the same methodologies as those used for other taxa. The second, well-supported strategy, is to protect entire habitats, and thus all the species contained within those environments. The third option could be to combine all information on fungi identified in environmental surveys and species databases into a central database, to consolidate all information of species population dynamics through time. Despite the continual growth in the literature and data on fungal diversity, the paucity of information on fungal species distributions remains the major barrier to the development of appropriate and accurate conservation efforts.

Fungi are vulnerable to the same biodiversity threats as many plants and animals, including habitat fragmentation, degradation and loss, climate change, nitrogen enrichment and pollution (Jönsson et al. 2017). While all types of ecosystem services - regulating, supporting, provisioning, and cultural services (Millennium Ecosystem Assessment 2005) - are provided by fungal activities, their actions in regulating terrestrial ecosystem processes are central to sustainable land use (Heijden et al. 2015). It is therefore possible that the loss of any, including those not yet unidentified, fungi may result in restricted performance of the most critical ecosystem services.

Over the last two decades, global conservation initiatives have shifted in focus, from being species centric, to an integrative habitat–ecosystem based approach (Heilmann-Clausen et al. 2015). Ecosystem-based approaches provide mycologists with the most opportunities to implement fungal conservation goals into broader scale conservation targets. Additionally, a broader ecosystem level approach may be the only achievable conservation method, due to the involvement of fungi in complex interactions with a plethora of other taxa (Nordén et al. 2020), thus making it impossible to successfully protect fungi on a species basis (Molina 2008). In light of this, Heilmann-Clausen et al. (2015) proposed 5 key criteria that could facilitate the incorporation of fungi into conservation actions: (1) as habitat and process providers for organisms of concern; (2) as indicators of ecosystem function trends; (3) as indicators of valuable habitats for conservation; (4) as a link between humans and the natural world through food, medicine, and biotechnical utility; and (5) as a source of novel solutions to conservation problems in other diverse organism groups. This ecosystem-level approach of habitat protection due to fungal hot spots has been achieved in England, with areas listed as 'Important Fungus Area' (IFA), including Pembury Walks (West Kent), which has almost 1,200 fungal species recorded (Ainsworth 2004).

Engaging mycologists in the work of conservation professionals, and recognizing the potential for the integration of mycology in broader conservation efforts would increase opportunities for research and increase interest in this field. Emphasis on the necessity for fungal conservation may help change the protection status of valuable habitats, and so also the preservation of all taxa. However traditionally, most of the research in the field of environmental mycology has been associated with taxonomy rather than ecology and conservation biology.

In Australia, the conservation of fungi also receives little recognition from a land management perspective, which is likely to reduce the probability that it will appear on subsequent conservation agendas. Reviews of the Management Plans of forty Australian National Parks revealed that 30% made no reference to fungi (Pouliot 2013, Pouliot et al. 2014). Of those that did mention fungi, over 90% made reference to pathogenic species, that is, only in the context of fungi posing a threat to other taxa. Only 25% referred to fungi in other contexts, but then usually only as an acknowledgement of their existence, or of the need for further research. In almost all cases, only a single reference was made to fungi, compared to an average of 109 references for plants and 83 for animals.

Determining the diversity of fungi for conservation

Determining the diversity of fungi is not without challenges. Only approximately 5% of species can currently be isolated as pure cultures (Manoharachary et al. 2005). This limits knowledge of what these organisms look like and how to survey their prevalence in the field. Basidiomycetes are difficult to identify in culture, and are often categorized with non-sporulating fungi as *mycelia sterilia* or as unknowns (Crawford et al. 2015). Thus the future of fungal detection and identification will be through DNA genome analysis (Raja et al. 2017).

Ideally, molecular methods should be used in conjunction with culture-based methods, where possible, for both practical and accurate quantification and identification. As the collective molecular sequence data available to mycologists is growing (Ryberg 2015), the combined value of the DNA sequenced along with taxonomic metadata with images, morphological descriptions and herbarium specimens, can greatly augment knowledge, and will likely benefit other areas of conservation (Lücking et al. 2020). Further, the pressure to discover new fungal species at a faster pace is mounting, with an estimated 90% of fungal species still undescribed (Hawksworth 2012). Up to 2011, approximately 1200 fungi were described each year; at this rate, it might take 4000 years to identify all species of fungi (Hibbett et al. 2011). However, the cost of DNA analysis has fallen dramatically, and amateur mycologists have managed to become involved as citizen scientists collecting specimens for DNA barcoding and depositing curated specimens in fungaria.

It is possible that species could become extinct before being described and named, but the identification of a primary fungal barcode marker for DNA and rRNA sequencing methodologies has revolutionized the way fungal communities are studied (Stielow et al. 2015). Enhanced conservation efforts should be achievable with these advances, potentially enabling insights into fungal communities that were previously unavailable (Bengtsson-Palme et al. 2013). A good example of this is the Global Spore Sampling Project (GSSP) which aimed to collect air samples across the world, and conduct DNA-based comparisons to compile information on fungal diversity at very large spatial scales proximal to the sampling location (Ovaskainen et al. 2020), since many fungi disperse by windborne spores. The project currently has 50 sampling locations distributed across all continents, with additional researchers encouraged to join.

Mycological education and research in academia

The nature of mycological research and education is changing, as with all disciplines. Research in all areas appears to be decreasing in intensity, despite the continued efforts of dedicated mycologists. If this is the case, the community of mycological professionals is losing potential new members to other, higher profile areas of science — potentially due to mycology rarely being included in tertiary courses, however this needs to be quantified.

Methodology

To determine the presence or absence of the extent to which mycological science is currently taught within University curricula, and to quantify the existing expertise within these tertiary institutions, a survey was conducted of all universities within the Australian states of Victoria and South Australia, which have a rich fungal biota with numerous endemic species (Buchanan & May 2003), and boast some of the highest ranked universities in the world. All data were collected in 2017, before the start of the 2018 academic year. Searches were conducted within the respective university websites, course handbooks and expert registers. This may not be the most exhaustive search; however the results effectively demonstrate the relative prominence of mycology across the studied institutions. The current work was constrained in both its time scale and geographical extent, building on previous work (Irga et al. 2018).

The presence/absence information gathered fell into three categories, depending on whether the search terms 'Mycology', 'Fungi', 'Fungal', 'Fungus', 'Mushroom' and 'Yeast' were present in: the name of a subject or course, the subject or course description, or profiles of researchers or academic staff.

This information was obtained through a combination of email correspondence with university administrative staff and general internet searches reviewing publicly available information on university websites.

In order to quantify the growing community interest in mycology, a manual search through social media platforms was conducted that pertain to mycology, with the same search terms as used above. For the purposes of this investigation, 'social media' refers to any web-based service that allow individuals, communities and organizations to collaborate, connect, and build a community by enabling them to generate and engage with user-generated content that is easily accessible (Toivonen et al. 2019). Numbers of members engaging with content on each of these platforms were recorded in March 2018 and in March 2020. Focus was placed specifically on social networking sites and content communities such as Facebook, Quora and Reddit, which are likely to contain relevant information for studying human-fungi interactions. Non-English speaking platforms such as VKontakte and Odnoklassiniki, and the Chinese QZone, could also be a source of mycological information sharing but were not referred to here.

Through the process of searching through social media platforms, we were made aware of successful community science initiatives that had their own websites, but had a strong social element. These identification sites are additionally presented and discussed.

Results

Mycology in academia

Of the 11 universities assessed, only one had a course with mycology or fungi as part of the name of a subject (Table 1) and this delivered content on the medical, clinical and pathological aspects of mycology. Just over 70% of the universities mentioned mycology and/or fungi within the formal descriptions of subjects, although most of these were not primarily mycological; they referred for example to microbiology, basic ecology, or clinical pathology. University biodiversity and conservation subjects and courses as observed in the current study (i.e Victoria, Australia and South Australia, Australia) tend to exclusively examine biodiversity and extinction as they relate to plants and animals, and the potential threats to ecosystem functioning and services if fauna or flora were removed: mycology appeared mainly to be taught in general biology subjects, where the curricula were limited to developing an awareness, and key characteristics of the kingdom. Interestingly, over 90% of universities listed a mycologist researcher or academic working at the institution.

Mycology in social media

Twenty social media groups related to mycology were identified, across Facebook, Quora and Reddit (Table 2), the most popular of which are ‘The Mushroom Identification Forum, Reddit mycology and Quora fungi. Every group increased participation over the two year study period, with a total of 528,854 individuals engaging with these platforms in 2020, and increase from 243739 in 2018.

Additionally, successful community science initiatives that had their own websites were identified:

- Mushroom Observer (MO) [https://mushroomobserver.org/]
- iNaturalist [https://www.inaturalist.org/]
- Fungimap [https://fungimap.org.au]
- Fungal Diversity Survey, formerly North American Mycoflora Project [https://fundis.org/]

Discussion

To ensure academic mycology flourishes and continues to provide research to inform conservation biology, the field needs to attract and retain talented people, improve communication with the public so as to attract research funding, and continue producing cutting-edge science. Better recruitment of mycologists is likely to be achieved by exposure to content at the undergraduate level. In doing so, mycology careers may be re-conceptualized, with mycology-focused graduates seeking employment in new sectors, which will help retention of early-career scientists. This can be achieved by providing opportunities, and then actively encouraging promising undergraduates to apply for post graduate positions and mentor them through applications. Mycology is a small field and suffers from an invisibility problem. Few people know what a mycologist is, and fewer have met one. This perception can be combatted by promoting interactions between existing mycologists, and convincing students that mycology is an important and rewarding career path. An additional barrier to careers in mycology is perception; perception that the careers are repetitive, laborious, and unrewarding, as has been the case for traditional careers in systematics and taxonomy. A key to countering these perceptions is to expose students to the diverse career pathways pursued by established mycologists. Current levels of mycological expertise in the Victoria and South Australia are inadequate to provide the necessary background research so as to support local fungal conservation.

Citizen science and social media networks

Fungal study groups meet and organize meetings through social media, usually through blogs, Facebook, Quora or Twitter (Table 2). These sites and platforms tend to provide resources about fungi, their relationships with other taxa and identification resources. The resources provided can be regionally based, or more general. The general aim of these groups is to educate and assist people with field identification and also (depending on interest and access to equipment) with microscopic examination, along with the active encouragement of interaction between members. Interactions such as this could leave a lasting legacy if people fall in love with mycology and outdoor experiences, become aware of the work done by other mycologists, or develop science-citizen relationships.

Concerning the decline in professional mycologists, there is potential that the resulting shortfall in education, skills and knowledge can be partially supplemented with voluntary contributions from amateur scientists and citizens, especially in regards to macro-fungi. Macro-fungi are appealing to ordinary people, which facilitates the inclusion of fungi in citizen science-based monitoring of biodiversity. Additionally, for exceptionally rare species, the search for macro-fungi by interested amateurs, under the guidance of professional scientists, might be the only cost-effective way to obtain records, as environmental sampling of very low frequency mycelia hidden in soil or other substrata is difficult to organise and fund. Citizen science has developed from its early conception as an educational tool into a significant contributor of empirical data in ecological research (Gallo & Waitt 2011). Citizen science engages and enables the public knowledge of species and conservation needs, with the concomitant provision of data that is of scientific value (Follett & Strezov 2015). A benefit of citizen science is that amateurs can participate at multiple levels depending on their time and experience. Citizen science projects offer mutually beneficial partnerships between scientists and non-scientists through the promotion of the participatory approach to mycology research in which citizens are not only considered as "data collectors", but as proper "scientists". Citizen science-based projects are helping to address challenges unique to mycology, such as high species richness and poorly resolved taxonomy (Watling 1996). By combining citizen science into the broad field of conservation mycology, there is an increase in human – nature interactions that can potentially integrate public outreach with data collection, filling the gap in diversity knowledge in mycology (Fig. 1)

Citizen science projects, especially using web platforms, require some degree of standardization, to ensure that the data generated is of the highest possible quality (Heigl et al. 2019). This appears to be the greatest barrier to its use, and remains one of the most discussed aspects of its implementation (Fritz et al. 2019). Solutions include volunteer training, continual data collection feedback over the duration of the project, comparison against data that has been professionally collected, validation by experts (Fritz et al. 2019), and use of standardized measurement tools (Kosmala et al. 2016).

Community-based learning

An additional beneficial component of citizen science-orientated projects is that they support community-based learning and a participatory research approach that involves citizens in scientific debate through community engagement, direct experience and informal education (Ballard & Belsky 2010). A community-based monitoring approach allows for more than just the collection of data, but enables the enhancement of ecological literacy and the public understanding of anthropogenic impacts on natural ecosystems (Whitelaw et al. 2003). Community-based monitoring promotes citizens' direct experience of the natural environment that contributes to community engagement and improves ecological awareness. The informal educational role of citizen science activities contributes also to the redesign of the standard process of knowledge production and to democratize science through sharing information between experts and non-experts (Conrad & Hilchey 2011). Even such grassroots mycology as the submission of incidence information and photos of fungi by citizens in their local area (Newbound et al. 2010) can provide valuable information on species distributions.

New technologies and social media offer opportunities to expand the democratization of science data sharing by making scientific information accessable to non-experts. Internet-based platforms and mobile applications have greatly simplified the recording of species observations, and are also widely used to store documentation such as photos and map distribution profiles. Recent advancements made in technology and communication have benefited amateur mycological studies through the facilitation and encouragement of global information sharing amongst amateurs, but also potentially with the professional community. There are some challenges that must be overcome to maximise what citizen science can offer mycology. In particular, the pressure of professional research and the lack of funding available for taxonomic work may lead some professionals to become concerned over a heavy reliance on amateur mycologists for their research.

The identified social media pages include collaborations with academics, experts and other citizens, who provide interactions such as commenting on photographs and providing identification assistance. This encourages a culture of engagement, as the photographer/uploader interacts with their community to create discourse and discussion on the identification collectively. Further, these groups organize local forays and the social media pages are where these forays tend to be announced. Fungal forays (haphazard screening of a specified area, recording species of interest within that area) represent the classic means of obtaining records or specimens of macro-fungi. However, there are significant limitations when social media platforms such as Facebook and Reddit are used for conservation. Some skill and/or privileged access is required in order to mine the text and pictures for research data. Also, there is no way to download a list of all the species that have been found and where from a Facebook page/group or a subreddit. Facebook and Reddit pages on mycology vary in quality: some perpetuate false information about mycology, the posts are not always corrected, and some posts focus on psilocybin mushrooms which are illegal in some countries.

The increased involvement of amateurs may require the reconsidering of traditional research questions and approaches, but will ultimately benefit the discipline. One of the main qualities of opportunistic foraying is that it is often the best way to record rarely fruiting species that may be missed using structured sampling methods (Halme et al. 2012, Halme et al. 2015). Irrespective of these challenges, any attempt to overcome data shortfalls and develop ways to break down the barriers to engagement with real-world mycological biodiversity is a priority for conservation, and thus paramount to further initiatives.

To this end, the use of specialized platforms that try to link all stakeholders in conservation mycology will have the most success. The top two specialized platforms of fungi identification are Mushroom Observer (MO) [https://mushroomobserver.org/] and iNaturalist [https://www.inaturalist.org/]. Both sites have a social element but are primarily about identifying species. iNaturalist is one of the most popular citizen science data portals in the world (Boone & Basille 2020). Users can submit pictures of biological observations to an online data base to be reviewed by the rich online community and used for important biodiversity research around the world. Users can use the iNaturalist ap to plan community projects and learn more about species identification and biodiversity. It uses a community-driven model to help identify species and experts to assist with both initial identifications and verify observations. The leadership of iNaturalist sees its primary function as social and educational, rather than scientific. At the time of writing, iNaturalist has approximately 13 million accounts of species ranging from fungi, plants, insects, and animals. Mushroom Observer is also guided by citizen science, albeit with a focus on macro-fungi (Moose et al. 2020), which assists researchers in linking images uploaded to geographical locations and enables an assessment and comparison of the morphological variability of the species in question. iNaturalist and MO allow downloading of all 'verified' observations for an area and the area can be defined. They offer the great advantage over social media groups of offering geographical location of fungal reports and thus being much more important for fungal distribution knowledge. Using these data, machine learning and visual recognition computer vision research can be applied to increase the rate and precision of identification (Sulc et al. 2020). Some apps (e.g. Fungal Diversity Survey: https://fundis.org/), and Australia's Fungimap: https://fungimap.org.au), targeting fungal citizen scientists have done more to address the data quality issues than others. Fungimap demonstrated a successful engagement model by working with regional fungi society groups, which gives volunteers and collaborating groups the support of a dedicated research coordinator working within a proven framework. A similar strategy is employed by Fungal Diversity Survey (FunDis for short), who have assembled a working group of mycologists and leaders in fungal conservation, with a focus of putting FunDiS into the service of tracking species for conservation.

Conclusion

The paucity of mycological research will unquestionably lead to poor conservation outcomes for fungi. This could potentially lead to the loss of species, even before they are named and their ecological niches are resolved. Whilst technological advancements in molecular investigative tools are allowing for an increased rate of species discovery, the lack of active professional mycologists is currently constraining progress.

The engagement and participation of citizen scientists is becoming an increasingly important factor in mycological research, which is currently being facilitated through social media. The synergy of these potentially competing forces through community-based learning and participatory research approaches (Fig. 2) has evolved to become the new frontier of mycological research and teaching, which should help fill gaps in this poorly resourced discipline. The main barriers for future engagement with this approach will be connecting amateurs with experts, and ensuring that crowdsourced online platforms are able to ensure data quality and species verification, highlighting the importance of integrated data validation processes for decision-making in environment conservation programs.

References

Ainsworth AM (2004) *BAP fungi handbook.* English Nature Research Reports No 600. Natural England. Windsor, Berkshire, UK. [www document] URL *http://publications.naturalengland.org.uk/publication/113017*

Allen JL, Lendemer JC (2015) Fungal conservation in the USA. *Endangered Species Research* 28: 33-42.

Arora D, Shepard GH (2008) Mushrooms and economic botany. *Economic Botany* 62: 207-201.

Ballard HL, Belsky JM (2010) Participatory action research and environmental learning: implications for resilient forests and communities. *Environmental Education Research*, 16: 611-627.

Barron ES (2011) The emergence and coalescence of fungal conservation social networks in Europe and the U.S.A. *Fungal Ecology* 4: 124-133.

Bengtsson-Palme J, Ryberg M, Hartmann M, Branco S, Wang Z, Godhe A, De Wit P, *et al* (2013) Improved software detection and extraction of ITS1 and ITS2 from ribosomal ITS sequences of fungi and other eukaryotes for analysis of environmental sequencing data. *Methods in Ecology and Evolution* 4: 914-919.

Boone M, Basille M (2020) Using iNaturalist to contribute your nature observations to science. EDIS [Fact Sheet], University of Florida. [www document]. URL https://journals.flvc.org/edis/article/view/107698

Boyles JG, Cryan PM, McCracken GF, Kunz TH (2011) Economic Importance of Bats in Agriculture. *Science* 332: 41-42.

Buchanan PK, May TW (2003) Conservation of New Zealand and Australian fungi. *New Zealand Journal of Botany* 41: 407-421.

Byrne AQ, Voyles J, Rios-Sotelo G, Rosenblum EB (2016) Chapter Nine - Insights From Genomics Into Spatial and Temporal Variation in Batrachochytrium dendrobatidis. In:

Progress in Molecular Biology and Translational Science, eds. M San Francisco, B San Francisco, pp. 269-290. Academic Press. URL https://www.sciencedirect.com/science/article/pii/S1877117316300138

Conrad CC, Hilchey KG (2011) A review of citizen science and community-based environmental monitoring: issues and opportunities. *Environmental Monitoring and Assessment* 176: 273-291.

Crawford JA, Rosenbaum PF, Anagnost SE, Hunt A, Abraham JL (2015) Indicators of airborne fungal concentrations in urban homes: Understanding the conditions that affect indoor fungal exposures. *Science of The Total Environment* 517: 113-124.

Dahlberg A, Genney DR, Heilmann-Clausen J (2010) Developing a comprehensive strategy for fungal conservation in Europe: current status and future needs. *Fungal Ecology* 3: 50-64.

Dahlberg A, Mueller GM (2011) Applying IUCN red-listing criteria for assessing and reporting on the conservation status of fungal species. *Fungal Ecology* 4: 147-162.

Davoodian N (2015) Fungal conservation in the United States: current status of federal frameworks. *Biodiversity and Conservation* 24: 2099-2104.

Field KJ, Daniell T, Johnson D, Helgason T (2020) Mycorrhizas for a changing world: Sustainability, conservation, and society. *Plants, People, Planet* 2: 98-103.

Fisher MC, Henk DA, Briggs CJ, Brownstein JS, Madoff LC, McCraw SL, Gurr SJ, (2012) Emerging fungal threats to animal, plant and ecosystem health. *Nature* 484: 186–194

Follett R, Strezov V (2015) An Analysis of Citizen Science Based Research: Usage and Publication Patterns. *PLoS ONE* 10, e0143687 https://doi.org/10.1371/journal.pone.0143687

Frick WF, Pollock JF, Hicks AC, Langwig KE, Reynolds DS, Turner GG, Butchkoski CM, *et al.* (2010) An Emerging Disease Causes Regional Population Collapse of a Common North American Bat Species. *Science* 329: 679.

Fritz S, See L, Carlson T, Haklay MM, Oliver JL, Fraisl D, Mondardini R, Brocklehurst M, Shanley LA, Schade S, Wehn U (2019) Citizen science and the United Nations sustainable development goals. *Nature Sustainability*. 2:922-30.

Gallo T, Waitt D (2011) Creating a Successful Citizen Science Model to Detect and Report Invasive Species. *BioScience* 61: 459-465.

Grube M, Gaya E, Kauserud H, Smith AM, Avery SV, Fernstad SJ, Muggia L, Martin MD, Eivindsen T, Kõljalg U, Bendiksby M (2017) The next generation fungal diversity researcher. *Fungal Biology Reviews* 31: 124-130.

Halme P, Heilmann-Clausen J, Rämä T, Kosonen T, Kunttu P (2012) Monitoring fungal biodiversity – towards an integrated approach. *Fungal Ecology* 5: 750-758.

Halme P, Holec J, Heilmann-Clausen J (2017) The history and future of fungi as biodiversity surrogates in forests. *Fungal Ecology* 27: 193-201.

Halme P, Kuusela S, Juslén A (2015) Why taxonomists and ecologists are not, but should be, carpooling? *Biodiversity and Conservation* 24: 1831-1836.

Hawksworth DL (2012) Global species numbers of fungi: are tropical studies and molecular approaches contributing to a more robust estimate? *Biodiversity and Conservation* 21: 2425-2433.

Heigl F, Kieslinger B, Paul KT, Uhlik J, Dörler D (2019) Opinion: Toward an international definition of citizen science. *Proceedings of the National Academy of Sciences* 23: 8089-8092.

Heijden MGA, Martin FM, Selosse MA, Sanders IR (2015) Mycorrhizal ecology and evolution: the past, the present, and the future. *New Phytologist* 205: 1406-1423.

Heilmann-Clausen J, Barron ES, Boddy L, Dahlberg A, Griffith GW, Nordén J, Ovaskainen O, Perini C, Senn-Irlet B, Halme P (2015) A fungal perspective on conservation biology. *Conservation Biology* 29, 61-68.

Hibbett DS, Ohman A, Glotzer D, Nuhn M, Kirk P, Nilsson RH (2011) Progress in molecular and morphological taxon discovery in Fungi and options for formal classification of environmental sequences. *Fungal Biology Reviews* 25: 38-47.

Irga PJ, Barker K, Torpy FR (2018) Conservation mycology in Australia and the potential role of citizen science. *Conservation Biology* 32(5):1031-1037.

Jackson PW, Kennedy K (2009) The global strategy for plant conservation: a challenge and opportunity for the international community. *Trends in plant science* 1;14: 578-80

Jönsson MT, Ruete A, Kellner O, Gunnarsson U, Snäll T (2017) Will forest conservation areas protect functionally important diversity of fungi and lichens over time? *Biodiversity and Conservation* 26, 2547-2567.

Kosmala M, Wiggins A, Swanson A, Simmons B (2016) Assessing data quality in citizen science. *Frontiers in Ecology and the Environment*. 14:551-60.

Le Breton TD, Zimmer HC, Gallagher RV, Cox M, Allen S, Auld TD (2019) Using IUCN criteria to perform rapid assessments of at-risk taxa. *Biodiversity and Conservation*. 30:863-83.

Lücking R, Aime MC, Robbertse B, Miller AN, Ariyawansa HA, Aoki T, Cardinali G, Crous PW, Druzhinina IS, Geiser DM, Hawksworth DL (2020) Unambiguous identification of fungi: where do we stand and how accurate and precise is fungal DNA barcoding?. *IMA Fungus*. 11:1-32.

Manoharachary C, Sridhar K, Singh R, Adholeya A, Suryanaraynan TS, Rawat S, Johri BN (2005) Fungal biodiversity: Distribution, conservation and prospecting of fungi from India. *Current science* 89: 58-71.

McMullan-Fisher SJM, May TW, Robinson RM, Bell TL, Lebel T, Catcheside P, York A (2011) Fungi and fire in Australian ecosystems: a review of current knowledge, management implications and future directions. *Australian Journal of Botany* 59: 70-90.

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-Being: Policy Responses.* Findings of the Responses Working Group. Island Press, Washington, DC.

Molina R (2008) Protecting rare, little known, old-growth forest-associated fungi in the Pacific Northwest USA: A case study in fungal conservation. *Mycological Research* 112: 613-638.

Moore A, Nauta SE, Evans SE, Rotheroe M (2008) Fungal Conservation: Issues and Solutions. Cambridge University Press.

Newbound M, McCarthy MA, Lebel T (2010) Fungi and the urban environment: A review. *Landscape and Urban Planning* 96: 138-145.

Nordén J, Abrego N, Boddy L, Bässler C, Dahlberg A, Halme P, Hällfors M, Maurice S, Menkis A, Miettinen O, Mäkipää R (2020) Ten principles for conservation translocations of threatened wood-inhabiting fungi. *Fungal Ecology*. 1; 100919. https://doi.org/10.1016/j.funeco.2020.100919

Ódor P, Heilmann-Clausen J, Christensen M, Aude E, van Dort KW, Piltaver A, Siller I, Veerkamp MT, *et al* (2006) Diversity of dead wood inhabiting fungi and bryophytes in semi-natural beech forests in Europe. *Biological Conservation* 131: 58-71.

Ovaskainen O, Abrego N, Somervuo P, Palorinne I, Hardwick B, Pitkanen JM, Andrew NR, Niklaus PA, Schmidt NM, Seibold S, Vogt J (2020) Monitoring fungal communities with the Global Spore Sampling Project. *Frontiers in Ecology and Evolution* 7 URL doi:10.3389/fevo.2019.00511

Panjabi RKL (1993) International law and the preservation of species: an analysis of the Convention on Biological Diversity signed at the Rio Earth Summit in 1992. *Dickinson journal of international law* 11: 187.

Peintner U, Schwarz S, Mešić A, Moreau P-A, Moreno G, Saviuc P (2013) Mycophilic or Mycophobic? Legislation and Guidelines on Wild Mushroom Commerce Reveal Different Consumption Behaviour in European Countries. *PLOS ONE* 8: e63926.

Pouliot A, (2013) Fungi and biodiversity conservation. *Park Watch* 253: 26-27.

Pouliot A, May T, McMullan-Fisher S, Buchanan P, Allison L, Packer J (2014) It's time for a global strategy for plant and fungus conservation [online]. *Australasian Plant Conservation: Journal of the Australian Network for Plant Conservation* 22.

Raja HA, Miller AN, Pearce CJ, Oberlies NH (2017) Fungal Identification Using Molecular Tools: A Primer for the Natural Products Research Community. *Journal of Natural Products* 80: 756-770.

Ryberg M (2015) Molecular operational taxonomic units as approximations of species in the light of evolutionary models and empirical data from Fungi. *Molecular Ecology.* 24: 5770-5777.

Sadiković D, Kuštera M (2013) *Fungal conservation: Protected species of fungi in South Serbia region. Biologica Nyssana* 4: 35-40.

Stielow JB, Lévesque CA, Seifert KA, Meyer W, Iriny L, Smits D, Renfurm R, et al (2015) One fungus, which genes? Development and assessment of universal primers for potential secondary fungal DNA barcodes. *Persoonia: Molecular Phylogeny and Evolution of Fungi* 35: 242-263.

Sulc M, Picek L, Matas J, Jeppesen T, Heilmann-Clausen J (2020) Fungi Recognition: A Practical Use Case. In *The IEEE Winter Conference on Applications of Computer Vision 2020* (pp. 2316-2324).

Suryanarayanan TS, Gopalan V, Sahal D, Sanyal K (2015) Establishing a national fungal genetic resource to enhance the bioeconomy. *Current Science* 109: 1033-1037.

Toivonen T, Heikinheimo V, Fink C, Hausmann A, Hiippala T, Järv O, Tenkanen H, *et al*. (2019) Social media data for conservation science: A methodological overview. *Biological Conservation* 233: 298-315

Watling R (1996) The amateur contribution within the Society, in: Sutton, B.C. (Ed.), A Century of Mycology. Cambridge University Press, pp. 81-104. ISBN: 0-521-57056-5

Whitelaw G, Vaughan H, Craig B, Atkinson D (2003) Establishing the Canadian Community Monitoring Network. *Environmental Monitoring and Assessment* 88: 409-418.

Willis KJ (2018) State of the world's fungi (2018) Report. State of the world's fungi 2018. Report. Royal Botanic Gardens, Kew. URL https://stateoftheworldsfungi.org/