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PERSPECTIVE

A way forward for wild fungi in international sustainability policy

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Abstract

A series of international sustainability policies currently in negotiation will shape biodiversity conservation for decades to come. However, discussions of current sustainability policy have a huge blind spot: the absence of *Fungi*, one of the eukaryotic Kingdoms. Wild fungi are a key component of natural ecosystems (e.g., through parasitic symbiosis), maintain soil fertility by decomposing organic matter, and facilitate uptake of water and nutrients through mycorrhizal association with plant roots, enhancing carbon sequestration. Moreover, the harvest, use, and trade of wild fungi are essential economic and cultural activities, supporting livelihoods and providing food and medicinal ingredients. Still, the sustainability of wild fungi use is hard to assess because there is a lack of attention from research, legislation, and society at large. Here, we present a way forward for including wild fungi in international sustainability policy. We layout four key steps to foster a much-needed policy and societal transformation: acknowledge the existence of *Fungi* as an independent Kingdom; tailor sustainability policy targets to include *Fungi*; implement comprehensive monitoring of wild fungi status and trends; and promote responsible use of wild fungi as a livelihood opportunity in rural areas. These steps can facilitate a transition toward better recognizing, valuing, and conserving the ecosystem services wild fungi provide.

KEYWORDS

biodiversity, conservation, development, fungi, neglected, soil, sustainability, trade

1 | BACKGROUND

Ongoing and severe biodiversity loss has put the environment at the heart of global public policy agendas. A series of recent or imminent international meetings and conventions (such as the 26th session of the Conference of the Parties [COP26] of the UN Framework Convention on Climate Change [UNFCCC], the 15th meeting of the Conference of the Parties [COP15] to the Convention on Biological Diversity (CBD), and the IUCN World Conservation Congress) will shape conservation of biodiversity for decades to come (Xu et al., 2021). Together, these international processes will provide a roadmap for the conservation of biological diversity into the future. However, these processes have a huge blind spot, the near-absence of one of the eukaryotic Kingdoms—*Fungi*—from their scope of action

FIGURE 1 **Examples of benefits provided by wild fungi**. **(a)** A half-dug Caterpillar fungus (*Ophiocordyceps sinensis*), a highly valued medicinal fungus, **(b)** several edible species in a rural market in Trimphu, Bhutan, **(c)** dances at the Genekha Mushroom festival, a cultural celebration of *Fungi* in Bhutan, **(d)** fire morels (*Morchella anthracophila*), an edible fungus (Table Mountain, WA, USA). Credit: © Daniel Winkler, www.mushroaming.com **(a–d)**

(Cao et al., 2021; Gonçalves et al., 2021). *Fungi* must be included in international sustainability processes if the full extent of nature's contributions to people is to be properly accounted for and conserved (Cao et al., 2021).

Conservatively, *Fungi* include between 2.2 and 3.8 million species, possibly even 12 million, playing diverse and critical ecological roles (Hawksworth & Lücking, 2017; Wu et al., 2019). *Fungi* are threatened by habitat decline, overexploitation, land use change, and climate change (Heilmann-Clausen et al., 2015). The harvest, use, and trade in wild fungi is one area that particularly impacts the conservation of *Fungi* but has thus far received little attention (Román et al., 2006). Wild fungi support economic activities and livelihoods, and supply cultural services, nutritious food, and vital medicinal ingredients (Boa, 2008; Fukushima et al., 2020; Román et al., 2006) (Figure 1). As such, the lack of knowledge of the extent and sustainability of the harvest, use and trade in wild fungi impacts our ability to fulfill the Sustainable Development Goals, especially in rural areas (Bonet et al., 2014; Pérez-Moreno et al., 2021a; Pérez-Moreno et al., 2021b; Román et al., 2006; Tibuhwa, 2013). A world where biodiversity is valued, conserved, and delivers benefits essential for all people cannot be realized if wild fungi are not included. Indeed, momentum is building for the inclusion of wild fungi in sustainability policy, as calls from different geographies and sectors showcase the need and urgency of considering *Fungi* in all aspects of biodiversity conservation (Gonçalves et al., 2021; Kuhar et al., 2018). In this Perspective, we lay out the benefits of wild fungi to people; the potential threats to sustainability of harvest, use and trade; describe the blind spot in current international policy with relation to wild fungi; and discuss a way forward that includes wild fungi in international sustainability policy.

2 | BENEFITS PROVIDED BY WILD FUNGI

Wild fungi are widely consumed by a diversity of animals, and humans have almost certainly been using fungi since they first evolved. The earliest records of people consuming wild fungi date back to the Upper Palaeolithic (Power et al., 2015). Edible fungi were used and highly valued in ancient Greek and Roman times, across Asia, Africa, and the Americas (Boa, 2008). Nowadays, harvesting and use

FIGURE 2 Sustainable Development Goals supported by the harvest, use, and trade in wild fungi. Credit: @tillallo_arts, Pen&Paper

of wild fungi for food or medicine contribute to maintaining traditional ethnomycological knowledge, which is an essential component of the identity of rural and indigenous communities around the world (Tibuhwa, 2013) providing an important cultural ecosystem service (i.e., nonmaterial benefits people derive from nature).

The harvest, use, and trade in wild fungi supports diverse Sustainable Development Goals and provides key provisioning ecosystem services such as food (SDG 2), medicines (SDG 3), and livelihoods (SDGs 1, 8, and 12; Figure 2) (Boa, 2008; Pérez-Moreno et al., 2021a,b; Román et al., 2006). Globally, more than 2180 species of wild fungi are used for food (Li et al., 2021). For medicinal fungi estimates are not available worldwide, but more than 1000 species have been recorded as being used in China alone (Wu & Yang, 2021). There has also been a considerable increase in the isolation of bioactive medicinal compounds, with key compounds found in more than 100 species (Pérez-Moreno et al., 2014). The value of international trade in these species has been steadily increasing over the last 15 years, such that in 2019, it involved 134 countries and a trade value of over 5.2 billion US dollars (UN Comtrade Dataset) (de Frutos, 2020). The level of wild fungi use and trade varies widely by region, in some places representing the seasonal primary livelihood for rural people (Pérez-Moreno et al., 2021a,b). It can be especially crucial for groups such as the elderly, the poor, and women, who may have few other livelihood options (Bonet et al., 2014). For example, in rural Tanzania and Mexico, women represent between 76% and 90% of fungal gatherers and vendors, respectively (Pérez-Moreno et al., 2008; Tibuhwa, 2013).

Moreover, wild fungi provide supporting ecosystem services because they maintain soil fertility by recycling nutrients through decomposition of organic matter (SDG 15). They also play a key role with their mycorrhizal association with plant roots, facilitating uptake of water and nutrients, and therefore enhancing carbon sequestration and storage (SDG 13). Furthermore, mycorrhizal fungi can influence forest structure and as such shape how some forest ecosystems respond to climate change (regulating ecosystem service) (Pennisi & Cornwall, 2020). Indeed, the ecological relevance of mycorrhizal fungi mycelial networks, the so called wood wide web, is driving increased scientific attention on their role in future forest dynamics (Pennisi & Cornwall, 2020).

3 | SUSTAINABILITY OF THE HARVEST, USE, AND TRADE IN WILD FUNGI

Wild fungi harvest, use, and trade can have direct and indirect sustainability impacts. Direct impacts relate to the sustainability of the target species. For most species studied so far, the harvesting of fungal reproductive structures (known as sporophores or fruiting bodies) has little direct measurable effect on future harvest or the species' sustainability, but the trampling of the forest floor when harvesting can significantly reduce the number of sporophores produced (Egli et al., 2006). This can be especially serious in small remnants of forest located close to urban centers where foraging pressure can be larger, and potential conflicts might appear between foraging and the conservation of species. However, empirical studies are severely limited in scope and time, so the effect of harvesting is not always straightforward to assess; further research is needed. For example, the decrease in production of caterpillar fungus (*Ophiocordyceps sinensis*) in the Himalayas has been linked to a combination of overexploitation and climate change, threatening the livelihood of the communities who depend on its harvest (Hopping et al., 2018).

Indirect sustainability impacts are associated with the collateral effects of fungi harvesting. For example, harvesting can result in soil compaction, disturbance of the humus layer, and direct soil exposure that can negatively impact some habitats, especially old-growth forests, or areas with little to no natural disturbance. This can lead to damaged plant roots, potentially contributing to a reduction in plant health and soil erosion. Even more destructively, native old-growth forests are deliberately burned in Chile to trigger the appearance of morels (*Morchella* spp.), under the unfounded assumption that burning stimulates reproduction—a trait of some species in the northern hemisphere that is not the case for species in Chile (Pildain et al., 2014). Similarly, agarwood trees (e.g., *Aquilaria malaccensis*) in Southeast Asia have been felled on a large scale for their resinous heartwood, which is used in luxury perfumes, cosmetics, and medicinal products. Heartwood is formed as the result of infection with fungi such as species of *Aspergillus*, *Botryodiplodia*, *Diplodia*, *Fusarium, Penicillium*, *Pythium*, or *Trichoderma* (Sangareswari Nagajothi et al., 2016).

The use of wild fungi also has health implications for humans. Misidentification and mislabeling of wild fungi is becoming apparent and permeating supply chains worldwide. Using DNA metabarcoding, a recent study found both potentially toxic and unidentified species in products labeled as containing “wild mushrooms” sourced from an online retailer with global shipping services and local grocery stores in the United States (Cutler et al., 2021). Unregulated trade of wild fungi could have significant public health consequences, as some fungus species are known to be poisonous and even deadly (Boa, 2008). Moreover, individual reactions or allergies to different fungi are poorly known and would be untraceable in foods with mixtures of identified and unidentified species.

4 | GOVERNANCE OF THE HARVEST, USE, AND TRADE IN WILD FUNGI

A general lack of regulatory attention to wild fungi limits the ability to monitor harvesting patterns, potentially resulting in overexploitation in some regions that could negatively impact ecosystem health (Dentinger & Suz, 2014). Overlooking *Fungi* within international sustainability policy ignores the fundamental ecosystem services provided by wild fungi and their trade. This could hinder progress toward sustainability goals and prevent improvement in the SDGs that the harvest, use, and trade in wild fungi supports. For instance, ignoring, or not explicitly including *Fungi* in international sustainability policy, can impede progress toward ecosystem-level conservation, as it does not consider the ecological role that wild fungi have in maintaining diverse natural ecosystems, and the potential direct and indirect ecological impacts posed by trade in wild fungi. Similarly, policies that overlook wild fungi’s contributions to people risk ignoring the role that trade in fungi has in providing food, livelihoods, and medicinal ingredients. As such, the neglect of *Fungi* by international sustainability policy implicitly excludes those who rely on wild fungi harvest, use and trade from its scope of action.

The potential risks of missing wild fungi in sustainability policies is linked to other international conservation processes and trade data sets still overlooking *Fungi*. Conservation status, for instance, most often based on IUCN Red List assessments, is frequently used to identify species that may be at risk of being traded unsustainably. However, only an estimated 0.4% of known fungal species (n = 474) had been assessed at a global level by the end of 2021, compared to 100% of birds (n = 11,162) and 91% of mammals (n = 5968) (IUCN, 2021a). For *Fungi*, the problem is twofold: the vast majority (~95%) of species are undocumented, and only a fraction of those documented have had their conservation status formally assessed (Heilmann-Clausen et al., 2015). Additionally, because trade data for wild fungi are aggregated at the Kingdom level by the FAO and the UN Comtrade Database (except for the genus *Agaricus*), it is difficult to monitor the trade in a particular species, or even a genus, and assess its sustainability. Altogether, the near-total omission of *Fungi* from the IUCN Red List and trade data sets means it is challenging to include the Kingdom in sustainability policy, because these data sets are used in many of the indicators for monitoring progress toward objectives (CBD, 2020).

5 | A WAY FORWARD

The neglected nature of our relationship with *Fungi* is not new. However, as current sustainability challenges force a reexamination of society’s priorities, a renewed relationship with nature must consider all domains of life on Earth. Including *Fungi* in international sustainability policy will require a societal shift toward better understanding, managing, and valuing of the ecosystem services that wild fungi and their trade provide and the

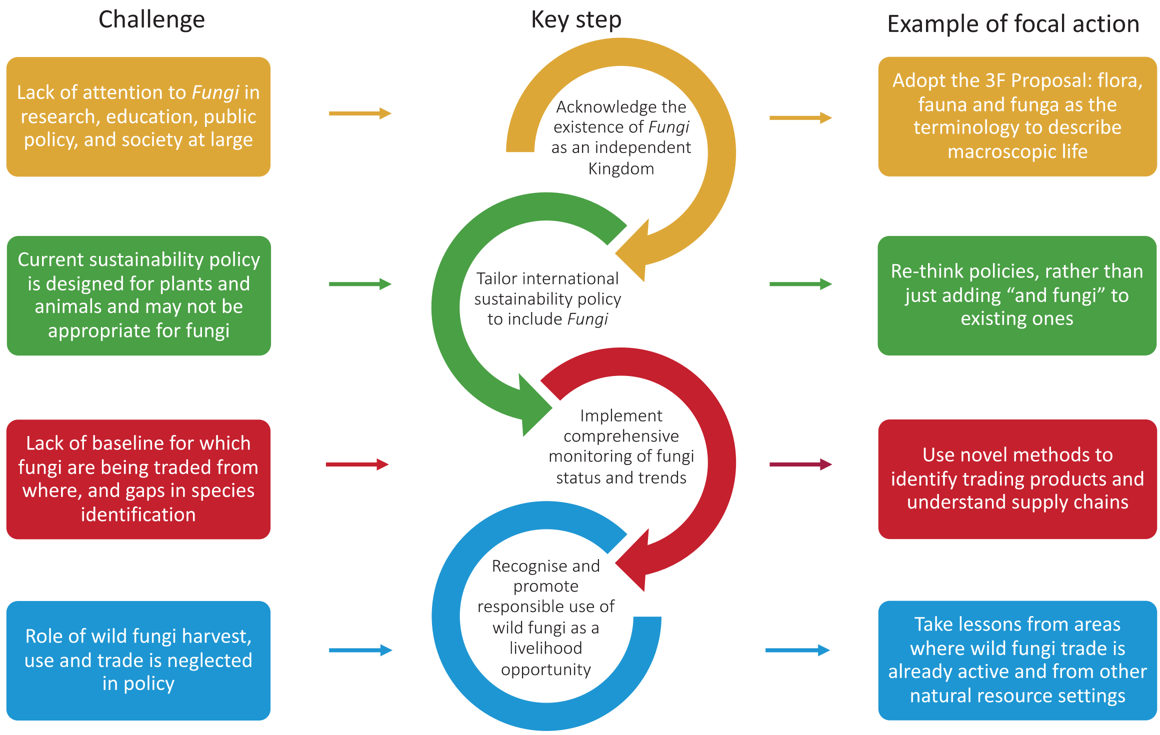

FIGURE 3 A way forward for wild fungi in international sustainability policy. Challenges, key steps, and examples of focal actions

SDGs they support. Moreover, a way forward for wild fungi in international sustainability policy will require cross-sectoral and cross-country collaboration (SDG 17). Sustaining wild fungi harvest, use, and trade needs a range of expertise, for which new alliances between policymakers, scientists, and entrepreneurs is paramount. Further, because trade in these species can be global, ensuring equitable trade will certainly need partnership between countries. Below, we present a series of necessary steps toward including wild fungi in international sustainability policy, highlighting potential cross-sectoral collaboration opportunities (Figure 3).

5.1 | ACKNOWLEDGE THE EXISTENCE OF *Fungi* AS AN INDEPENDENT KINGDOM IN RESEARCH, LEGISLATION, AND SOCIETY AT LARGE: THE 3F PROPOSAL

While *Fungi* has been considered an independent Kingdom since at least 1969 (Whittaker, 1969), universities, multilateral biodiversity agencies, governments, and society at large still fall short in recognizing *Fungi* as an independent form of life on Earth. For example, although in the United States there has been a steady abandonment of organismal-based structures in institutions of higher education, to our knowledge there has never been a unit dedicated to Mycology at the equivalent of a department in US universities or colleges. Instead, Mycology has historically been included as a part of other departments organized around plants, microbes, or applied sciences. This inaccuracy is more than semantic and has real-world consequences. For example, grants and funds that support scientific research are very rarely tailored to the study of fungal sustainability and the ecosystem services wild fungi provide. Indeed, only 1–2% of articles indexed in Web of Science (between 1991 and 2010) under the topic "environment" mentioned fungi (Pautasso, 2013).

Likewise, national governments usually fail to acknowledge *Fungi* in legislation, missing the impacts that projects might have on fungal sustainability. For instance, Chile is the only country in the world that includes wild fungi in impact evaluation assessments for economic developments projects. Moreover, legislation around the harvesting, exportation, or importation of *Fungi* for scientific purposes in most of the relevant government agencies (e.g., Animal and Plant Health Inspection Services in the United States) lacks language that specifically addresses *Fungi*.

Evidence of the pervasiveness of the blind spot with respect to *Fungi* is the extensive use of incomplete terminology referring to macroscopic life on Earth—flora and fauna—which entirely fails to acknowledge organisms of Kingdom *Fungi*. This happens within sustainability policy, but also in universities, governments, NGOs, and society at large. To start moving away from this severe neglect of *Fungi*, we encourage the formal adoption of the 3F proposal in which we refer to flora, fauna, and funga as the correct and modern terminology to describe macroscopic life (see https://www.faunaflorafunga.org/) (Kuhar et al., 2018).

5.2 | TAILOR INTERNATIONAL SUSTAINABILITY POLICY TO INCLUDE *Fungi*

The lack of attention to *Fungi* precludes the creation of baseline documentation to develop the necessary targets, indicators, and monitoring mechanisms for wild fungi within international sustainability policy. This requires including wild fungi more fully into IUCN's Red List and global trade data sets at the appropriate level of resolution, so that trade and other threats can be tracked and mitigated (Marsh et al., 2021) Some positive steps toward this include the Global Fungi Red List Initiative (http://iucn.ekoo.se/en/iucn/welcome—that has considerably ramped up annual rates of threat assessments for fungi), the formation of a Fungi Conservation Committee within the IUCN Species Survival Commission (and a number of Specialist Groups for particular groups of fungi) along with the recent commitment by IUCN to incorporate *Fungi* in conservation strategies and communications (IUCN, 2021b).

Indicators, targets, and goals used in international sustainability policy were designed for plants and animals and may not be appropriate for *Fungi* in their current form. They will need revisiting, carefully accounting for the heterogeneity of species and forms, parts, and products from the same species that may be difficult to identify and that may be sustainably or unsustainably traded. Furthermore, those responsible for enforcing wildlife trade regulations often struggle with identifying taxa that are highly diverse and traded in a form that is difficult to identify to species or even genus level (Roberts & Hinsley, 2020). Wild fungi are notoriously difficult to identify using morphology alone, which means that enforcement of their trade and verification of legality will be extremely challenging unless further steps are taken. For instance, it may be necessary to include "look-alike" species into wildlife trade regulations such as CITES (Convention on the International Trade of Endangered Species of Wild Fauna and Flora). These species are not threatened by trade but are indistinguishable from closely-related species that are threatened. "Look-alike" listings are already in place for plant species-rich groups such as orchids. However, difficulties in identification may impede the transport of *Fungi* for sustainable, legal trade or vital scientific research (Hawksworth & Dentinger, 2013). Therefore, inclusion of *Fungi* into sustainability policies will require existing regulations, targets, and indicators to be rethought rather than just adding the term "and fungi" to existing text. Doing so will require mycologists with expertise in different traded groups to be consulted. For example, the CITES Plants and Animals Committee meetings are held to provide decision-makers with taxon-specific technical information from a range of scientific experts; the inclusion of *Fungi* may require a new Fungi Committee to ensure that fungal species are fully represented.

5.3 | IMPLEMENT COMPREHENSIVE MONITORING OF WILD FUNGI STATUS AND TRENDS

One practical solution that could be implemented at national and subnational levels is molecular, DNA-based identification of traded products. It has been shown that globally traded wild fungi products often contain mixtures of many species (Dentinger & Suz, 2014). Much like monitoring adulterants or spoilants for food safety, government agencies already involved in regulating commercial products should include molecular identification of fungi products as standard practice. Lessons could be learned from forensic analysis of trade in fish, where easy-to-use and relatively inexpensive tools have been developed and implemented (Ogden, 2008). This would enable a baseline to be established for which wild fungi are being traded from where, and would enrich the reference database used to identify fungal species, enhancing our ability to identify and track their trade in the future. Assessing traded products can complement and enhance monitoring of species in the field, which is key to understanding threats to and trends in wild fungi populations. Agencies that do not have the internal capacity to perform such analyses could easily partner with mycologists in academia and industry. Furthermore, this could inject much-needed resources to fill the gap in documenting fungal diversity, especially if recognized and funded as an essential component of regulatory competence.

5.4 | RECOGNIZE AND PROMOTE RESPONSIBLE USE OF WILD FUNGI AS A LIVELIHOOD OPPORTUNITY IN RURAL AREAS

Recognizing the role of wild fungi harvest, use, and trade in people's lives is key to ensuring that benefits (including for nutrition, food security, livelihoods, and health) are maintained and enhanced. Moreover, responsible use can contribute to the conservation of threatened species. This has been widely documented in other kingdoms (e.g., *Vicugna vicugna* population recovery through sustainable fiber production; IUCN, 2021a). Responsible use requires good harvesting practices such as the use of baskets that allow for spore dispersal, cutting the stipe with a knife to avoid pulling up the mycelium or gently twisting to detach the fruiting body from the mycelium, and cleaning of the fungi in situ. These practices should be adopted in all fungus use contexts (rural and urban). Promoting responsible use can be enhanced by empowering women, who are more commonly involved in the activity in rural areas, through creating local women's cooperatives for the commercialization of wild fungi. This can also serve as a structure for value-addition and technology transfer between harvesters and scientists, further increasing income of rural communities. Exploring options for bringing more species of wild fungi into cultivation could also be of benefit.

Promoting responsible trade in wild fungi will require the development of appropriate market channels, formal labor regulations, new governance structures and capacity building at the local level to accurately identify species, and sustainable management and commercialization skills (e.g., FairWild's certification scheme for fungi). Commercial harvesting of wild fungi can involve long trips, handling sharp objects, and power imbalances in which harvesters are dependent on intermediaries (Boa, 2008). Attention will need to be paid to the equitable sharing of benefits from trade so disadvantaged groups are not excluded. Understanding power relationships and differential access to benefits from fungal resources is key to avoiding elite capture, especially along supply chains that can stretch across continents. Where consumption is in distant places, care will be needed to protect against overconsumption driven by the high value of fungi created in markets distant from the area of harvest. Moreover, adequate safeguards will be needed along the supply chain to prevent misidentified products from entering the market. Learning from areas with active trade in wild fungi (such as Mexico, Tanzania, China, and Chile) and from other natural resource settings can serve as a starting point to developing solid sustainability science, which can inform the design of policy and management to promote the responsible harvest of wild fungi.

Finally, promoting sustainable use of wild fungi needs to consider the diversity of cultural, social, political, and economic realities of the countries where wild fungi are used. This diversity could be systematically acknowledged by promoting national and local codes of conduct developed jointly by local scientists, policymakers, local harvesters, and leaders. This will be of paramount importance in preserving ethnomycological biocultural spots where fungal harvesting knowledge and practices have developed over millennia (e.g., China and Mexico).

6 | CONCLUSION

Including wild fungi, and particularly their harvest, use, and trade, into international sustainability policy can serve as an avenue to promote *Fungi* by incentivizing an inclusive language, stimulating basic science, and highlighting their role as providers of ecosystem services and supporters of several Sustainable Development Goals. This will undoubtedly involve challenges, as the trade in wild fungi needs to be conceptualized and approached differently to the trade in plants and animals. However, parallels and lessons learned could be drawn from trade in plants and animals to inform this process. Including *Fungi* whenever the natural world is referred to would be a critical first step to acknowledging this Kingdom properly. Indeed, a transformation in research, education, public policy, and society at large will be required to finally place the *Fungi* Kingdom where it belongs—at the heart of sustainability policy and practice.

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