Fungal Ecology Special Issue: Editorial

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Fungal ecology stands in a peculiar niche between microbial and community ecology. With the booming popularity of microbiome and other omics technologies, bacteria have increased their dominance in the microbial ecology field [1, 2], while traditional ecologists continue to favor plant and to some extent animal models [3–5]. It thus appears that fungi and other unicellular eukaryotes (UE) have been left in the ever-widening discipline schism. This is not to say that interest in fungal ecology is fading, but that the current literature is a lot more disparate in terms of approaches and techniques used. The ultimate driving force moving fungal ecology forward is the need to understand all of the forces of nature that support and sustain life.

Fungi and UE continue to present significant challenges for taxonomic and phylogenetic identification [6]. A major underlying need of fungal ecology is to have a strong base of taxonomy and this has certainly come with all the advances made in nucleic acid sequence technology. In fact, some researchers have put too much reliance on these techniques to the complete exclusion of employing classical methods in fungal isolation and characterization. While bacterial microbiome studies enjoy relatively reliable taxonomic identification from 16S rDNA gene and even metagenomic sequencing, mycobiome studies remain few and far between, with limited taxonomy solving power. Indeed, phenotypic and culture-based studies remain an invaluable tool for fungal biology and ecology [7]. Of course, the advantage of having these organisms in pure culture is that they can be handled and studied in virtually all aspects of their biology which, in fact, may help in understanding how they function in their natural ecological settings. Thus, many challenges remain in examining the hundreds of niches of the planet where

fungi may have taken up residence, not only in demonstrating their existence in these niches but trying to have them in pure culture and appropriately stored for further study. Of note, fungi and UE have not been popular models to test ecological theories. This is due to their small size, disparate distribution, metabolism, and technical challenges for controlled experiments.

It is also likely that fungal ecology needs to stay between these two general fields because fungi and UE are important for reasons that are shared between these two research fields:

- Fungi directly and indirectly participate in feeding us.
- Fungi and UE are crucial drivers of soil and plant health.
- Fungi and UE are implicated in fermentation and nutrient cycling in all ecosystems.
- Fungi and UE can cause spoilage and diseases.

The diversity and distribution of fungi continues to be explored in environments from soil [8, 9] to freshwater [10] and our oceans [11]. Specific emphasis continues to be given to plant-fungal interaction, especially mycorrhizae [12–16]. Other symbiotic or non-symbiotic interactions are increasingly studied [17], with the “zombie ants” disease caused by *Ophiocordyceps unilateralis* being an extremely popular example [18].

Just as important in understanding the ecology of any organism is how it is able to function in the niches that it occupies. Significant research and development efforts are directed to the continued improvement of yeasts for food fermentation [19], in particular bread and wine making [20–23].

With this approach may come the discovery of new and totally unexpected fungi and their corresponding natural products. As an example, it is now known that plants have a microbiome, but the flora of this biome largely consists of various fungal species [24, 25]. Only a small portion of the 350,000 plant species that exist have been examined for the constituents of their biome [26–28]. And in fact, only a handful of species have ever been examined for their complete microbiome which consists of the entire make-up of

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the plant including roots, shoots, leaves, flowers, and fruits, and the network of relationships between these different compartments' microbiome has only begun to be unraveled [29]. A closer look at one fungal endophytic species, *Asco-coryne sarcoides*, revealed that it produces hydrocarbons that have biofuel potential and the completed genomic analysis of this organism represents a first for fungal endophytes [30]. Other endophytes have been examined for their fuel potential and it seems to be a promising area of research with enormous potential for helping to solve issues related to our need for liquid fuel and an ever increasing need to reduce carbon dioxide in the atmosphere [31, 32]. Thus, the broad approach of fungal ecology should represent efforts to understand how the organism is able to live in its environment, which may lead to completely unexpected results that have wide ranging implications and applications.

This special issue compiles recent findings in several areas of research, starting with endophytes. Saxena et al. provide a review of the ecological and potential industrial and agronomic use of members of the genus *Muscodora* [33]. Oita et al. report that endophyte diversity is likely best assessed by combining culture and high-throughput sequencing [34]. Bao et al. describe host-dependent response to endophyte colonization towards grass parasitism [35]. Xie et al. report on the beneficial impact on peanut soil parameters from *Phomopsis liquidambaris* inoculation [36]. Finally, Win et al. report plot-to-plot variation in tea plant-associated endophytes, but no significant impact of pesticides [37].

In keeping with the role of fungi in agricultural ecosystems, several papers address ecology and distribution in different cultures. Cureau et al. provide extensive surveys of the fungal diversity in soil, leaves, and grapes from a range of locations, varieties, and growth years for table and wine grapes grown in a distinct agricultural area in the Southern US [38]. Shi et al. report spatiotemporal differences in dynamics and composition of the fungal rhizosphere in cotton fields from arid Northwest China [39].

Next, several articles focus on different aspects of mycorrhizal and soil fungal ecology. Ferreira et al. report results from microcosm experiments supporting a model where soil microbial diversity modulates the plants' root colonization by arbuscular mycorrhizal fungi (AMF) [40]. Dos Passos et al. report diversity and composition of AMF in the Brazilian dry forest and describe several geological and plant host drivers [41]. Rodrigues et al. studied the diversity of AMF in a Brazilian conservation unit of Atlantic forest areas and report that natural regeneration increased AMF diversity [42]. Birhane et al. report on the diversity of AMF in fragmented natural forest remnants (Birhane et al., 2021). Kellog et al. tested the ability of quinoa to form AMF symbiosis and report limited association between AMF and roots [43]. Romero-Olivares conducted an in silico analysis to associate several terrestrial nutrient cycle traits with fungal

genes [44]. And finally, Pereira et al. describe the effect of *Acacia* invasion in deciduous forests on the microbial litter decomposition.

The fungal diversity in unusual hosts and environments remains a popular topic. Ogaki et al. describe the fungal diversity of sediments from deep-sea [45] and Rosa et al. describe airborne fungal diversity [46] using metabarcoding. Pino-bodas et al. report a survey of the *Cladonia* photobiont global biodiversity [47]. Morrison et al. describe the composition and potential metabolic roles of bacterial and fungal communities in tropical peatlands [48]. Huang et al. describe a correlation between soil fungal diversity and dissolved organic matter in semi-arid regions [49]. Borruso et al. describe the association between soil composition and Indri lemur gut mycobiota, highlighting the importance of geophagy in lemur digestive processes [50].

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