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Opinion Article

The next generation fungal diversity researcher

Martin GRUBE[a,*], Ester GAYA[b], Håvard KAUSERUD[c], Adrian M. SMITH[d], Simon V. AVERY[e], Sara J. FERNSTAD[f], Lucia MUGGIA[g], Michael D. MARTIN[h], Tove EIVINDSEN[h], Urmas KÕLJALG[i], Mika BENDIKSBY[h]

[a]Institute of Plant Sciences, University of Graz, Holteigasse 6, 8010, Graz, Austria
[b]Jodrell Laboratory, Royal Botanic Gardens, Kew, TW9 3DS, UK
[c]Section for Genetics and Evolutionary Biology, Department of Biosciences, University of Oslo, PO Box 1066 Blindern, NO-0316, Oslo, Norway
[d]Unilever R&D, Colworth Science Park, Sharnbrook, Bedfordshire, MK44 1LQ, UK
[e]School of Life Sciences, University of Nottingham, University Park, Nottingham, NG7 2RD, UK
[f]Department of Computer and Information Sciences, Northumbria University, Newcastle upon Tyne, UK
[g]University of Trieste, Department of Life Sciences, via Giorgieri 10, 34127, Trieste, Italy
[h]NTNU University Museum, Norwegian University of Science and Technology, NO-7491, Trondheim, Norway
[i]Institute of Ecology and Earth Sciences, University of Tartu, Tartu, Estonia

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ABSTRACT

Fungi are more important to our lives than is assumed by the general public. They can comprise both devastating pathogens and plant-associated mutualists in nature, and several species have also become important workhorses of biotechnology. Fungal diversity research has in a short time transcended from a low-tech research area to a method-intensive high-tech discipline. With the advent of the new genomic and post-genomic methodologies, large quantities of new fungal data are currently becoming available each year. Whilst these new data and methodologies may help modern fungal diversity researchers to explore and discover the yet hidden diversity within a context of biological processes and organismal diversity, they need to be reconciled with the traditional approaches. Such a synthesis is actually difficult to accomplish given the current discouraging situation of fungal biology education, especially in the areas of biodiversity and taxonomic research. The number of fungal diversity researchers and taxonomists in academic institutions is decreasing, as are opportunities for mycological education in international curricula. How can we educate and stimulate students to pursue a career in fungal diversity research and taxonomy and avoid the situation whereby only those few institutions with strong financial support are able to conduct excellent research? Our short answer is that we need a combination of increased specialization and increased collaboration, i.e. that scientists with specialized expertise (e.g., in data generation, compilation, interpretation, and communication) consistently work together to generate and deliver

* *Corresponding author.*
E-mail address: martin.grube@uni-graz.at (M. Grube).
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new fungal knowledge in a more integrative manner – closing the gap between both traditional and modern approaches and academic and non-academic environments. Here we discuss how this perspective could be implemented in the training of the 'next generation fungal diversity researcher'.

1. Fungi and their importance

Fungi are ubiquitous and essential components of all ecosystems on earth. Saprotrophic fungi are among the major nutrient recyclers (Boddy *et al.*, 2007). Mycorrhizal fungi have crucial impacts on terrestrial ecosystems through their symbiosis with higher plants, enhancing photosynthesis as well as the host plant's water and nutrient uptake (Smith and Read, 2008). Endophytic fungi, growing symptomless inside plants, have diverse beneficial effects to their hosts (Rodriguez *et al.*, 2009). In general, fungi directly and indirectly support human welfare through provision of diverse ecosystem services (Stajich *et al.*, 2009). In addition to the many 'do-gooders', an extremely diverse group of parasitic and pathogenic fungi can have devastating impacts on the ecosystem. Whilst fungi provide a myriad of medicines and food products, they also comprise species responsible for spoilage of food and materials, and represent direct threats to human health (Meyer *et al.*, 2016). Despite their importance to the environment and our lives (Fig. 1), the vast majority (>95 %) of fungal diversity remains undetected and much of the detected fraction lacks scientific names (Hibbett *et al.*, 2016). This applies to different levels, including yet undiscovered deep lineages of fungi as well as cryptic diversity within species (Lücking *et al.*, 2014) or even among genetically uniform individuals within a single strain (Hewitt *et al.*, 2016).

Major gaps in our knowledge of fungal diversity place us in a difficult situation as we face growing environmental challenges. Climate change, for example, is expected to have an extensive impact in natural ecosystems with direct consequences in the poorly understood mycota and increased threats from fungi habitat loss (Ainsworth *et al.*, 2015). While known and already named species can become subjects of red lists and conservation efforts, a vast diversity of unknown fungi could go extinct without notice. Other fungi may increase in abundance with unsolicited consequences, such as emerging fungal diseases of plants and animals (Garcia-Solache and Casadevall, 2010; Fisher *et al.*, 2012; Lorch *et al.*, 2016), or disruptions of food supply chains by fungal spoilage (Chakrabotry and Newton, 2011). Health problems can escalate rapidly. Fungal pathogens are currently causing more deaths than drug-resistant tuberculosis and malaria (Barnes and Rautemaa-Richardson, 2014; Calderone *et al.*, 2014; Denning and Broomley, 2015) and are prevalent in the chronic-wound microbiome (Kalan *et al.*, 2016). Environmental change will certainly also affect symbiotic systems that maintain ecosystem stability, such as mycorrhizal fungal associations or endophytes (Kivlin *et al.*, 2013; Treseder *et al.*, 2016), and even lichen-dominated habitats (Ellis and Yahr, 2011).

Given the importance of fungi, it is surprising to see a decline in mycological education and general emphasis on fungal diversity research and taxonomy at academic institutions. Experts in "phenotype-based" fungal taxonomy and systematics (i.e. those few that can recognize fungal species without DNA sequencing) are becoming a threatened race (Buyck, 1999). Fortunately, this knowledge is maintained to some extent among amateurs. At most universities, fungal biology represents only a small component of the overall academic training. Bachelor degree courses in fungal biology are rare, and mycology is often only a part of botany or microbiology courses and degrees. Mycology started out as an obscure sub-discipline of botany and although we realised long ago that plants and fungi are distantly related, in many ways mycology has continued to live in the shadow of plant science. In this environment, fungal biology teachers are underexposed to society, except in a few institutions. Too often, fungal diversity researchers and taxonomists have a limited domain of action, reduced to the dimensions of the so-called academic ivory towers. In contrast with a clear regression in fungal biology education, the field of fungal research is thriving in many aspects, as exemplified below.

In this opinion paper, we provide a summary of historic and current challenges and prospects in fungal diversity research and taxonomy, and put forward some suggestions for how the next generation fungal diversity researcher should be trained and work most effectively to fulfil the future needs of society.

2. Challenges and prospects of working with fungi

A very basic reason for the large gaps in our knowledge of fungi is that most fungi spend the majority of their life cycle belowground or within other substrates in their microbial phase, invisible to the naked eye. Moreover, a large proportion of fungi, especially in the early diverging branches of the fungal tree of life, do not produce macroscopic fruit bodies or fruit bodies at all. In the pre-DNA era, most knowledge about fungal diversity and ecology was acquired by recording and examining reproductive structures using imaging techniques (e.g., light and electron microscopy). In the second half of the last century, chemical profiling and various culture-based techniques (including mating studies and vegetative incompatibility tests), became more important. These techniques continue to provide relevant phenotypic and physiological information about fungal diversity, however, their use remains limited to fungi with macroscopically and microscopically diagnosable features or those able to grow *in vitro*.

With the introduction of PCR and Sanger sequencing techniques in the early 1990s, genetic tools made it possible to study fungi beyond the classic methodologies. Approaching