Biodivers Conserv (2007) 16:1–5
DOI 10.1007/s10531-006-9117-7

ORIGINAL PAPER

Fungal biodiversity: what do we know? What can we predict?

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Received: 30 December 2005 / Accepted: 14 August 2006 /
Published online: 18 January 2007

Abstract Although fungi are among the most important organisms in the world, only limited and incomplete information is currently available for most species and current estimates of species numbers for fungi differ significantly. This lack of basic information on taxonomic diversity has significant implications for many aspects of evolutionary biology. While the figure of 1.5 million estimated fungal species is commonly used, critics have questioned the validity of this estimate. Data on biogeographic distributions, levels of endemism, and host specificity must be taken into account when developing estimates of global fungal diversity. This paper introduces a set of papers that attempt to develop a rigorous, minimum estimate of global fungal diversity based on a critical assessment of current species lists and informed predictions of missing data and levels of endemism. As such, these papers represent both a meta-analysis of current data and a gap assessment to indicate where future research efforts should be concentrated.

Keywords Species lists · Ratio data · Endemism · Host specificity · Diversity estimates

Fungi are among the most important organisms in the world, not only because of their vital roles in ecosystem functions, but also because of their influence on humans and human-related activities (Mueller and Bills 2004). Fungi and fungus-like groups (e.g., water molds of kingdom Straminipila and slime molds and relatives of kingdom

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Protista) encompass an astounding breadth of taxa, morphologies (ranging from amoeba-like protists and single-celled aquatic chytridiomycetes to large basidiomycete mushrooms), ecologies, and life history strategies. Yet, only limited and incomplete information is currently available for most species and current estimates of species numbers for fungi differ significantly (Table 1).

The 1.5 million species hypothesized by Hawksworth (1991, 2001) is a commonly used figure (e.g., SA2000 1994). If this estimate is correct, less than 5% of the fungi have been described. Rossman (1994) queried a number of mycologists to develop a putative estimate of diversity for major taxonomic groups of fungi. This exercise resulted in a total estimate of over 1 million species of true fungi, with current knowledge of individual groups ranging from less than 1% for hyphomycetes to 67% for lichenized fungi (Table 2). At the current rate of new species descriptions, 1,000–1,200 fungi/year (Hawksworth 2001), it will take 1,000 years to describe the over 1 million missing species if these estimates are correct.

This lack of basic information on taxonomic diversity has significant implications for many aspects of evolutionary biology, e.g., phylogenetic hypotheses, the role that biodiversity plays in providing resilience to perturbations, coevolutionary relationships and processes, interpretations of biogeographic patterns, natural products screening programs, etc. (Mueller and Bills 2004; Hawksworth and Mueller 2005). Having a stable and accepted estimate of taxonomic diversity for fungi is also necessary to enable fungi to be included in considerations of biodiversity conservation, land-use planning and management, and related subjects. Even so, there have been few attempts to compile available information on fungal diversity or to use these data to rigorously estimate global diversity for fungi.

The commonly used figure of 1.5 million estimated fungal species is based primarily on the observed ratio between flowering plant diversity and fungal diversity in countries where fungi have been sufficiently well studied to enable a reasonable estimate of true diversity (Hawksworth 1991, 2001). David Hawksworth (1991) reported a 1:5–1:7 ratio of plant species to fungal species for Finland,

Table 1 Recent published estimates of fungal species diversity (expanded and modified from Table 2 in Hawksworth 2001)

Author	Date	Estimated species in millions (comments)
Pascoe	1990	2.7
Hawksworth	1991	1.5
Hammond	1992	1
Smith and Waller	1992	1 (on tropical plants alone)
Hywel-Jones	1993	1.5 (insect fungi awaiting discovery only)
Rossman	1994	1
Dreyfuss and Chapela	1994	1.3 (endophytes alone)
Hammond	1995	1.5
Shivas and Hyde	1997	0.27 (plant pathogens alone)
Aptroot	1997	0.04–0.07 (world ascomycetes alone)
Cannon	1997	9.9
Guzmán	1998	0.2 (for Mexico only)
Fröhlich and Hyde	1999	1.5+ (very conservative)
May	2000	0.5
Arnold et al.	2000	1.5+
Crous et al.	2006	0.17 (for South Africa only)

Table 2 Major groups of fungi and estimated world species numbers as compiled by Rossman (1994) compared to numbers reported in Hawksworth et al. (1995)

Group	Estimated species	Dictionary of fungi	Percent known
Aphyllophorales s. lat.	20,000	3,253	16
Macrolichens	20,000	13,500	67.5
Agaricales s. lat.	80,000	6,000	7.5
Dermatiaceous and aquatic hyphomycetes	80,000	350	0.4
Uredinales	50,000	7,000	14
Hypocreales and Xylariales	50,000	1,657	3
Ustilaginales	15,000	950	6
Gasteromycetes	10,000	892	9
Erysiphales	10,000	437	4
Jelly fungi s. lat.	5,000	285	6
Pezizales	3,000	1,029	34
Myxomycetes	1,500	760	50
Endomycetales (true yeasts)	1,000	273	27
Non-dematiaceous hyphomycetes	200,000	11,000	5.5
Coelomycetes	200,000	9,000	4.5
Other perithecioid ascomycetes	100,000	7,461	7.5
Helotiales	70,000	2,036	3
Insect-specific fungi	50,000	750	1.5
Crustose lichens	20,000	In macrolichens	
Mucorales	20,000	299	1.5
Oomycetes	20,000	760	4
Chytridiomyetes	20,000	793	4
Endogonales and Glomales	1,000	181	18
Total	1,028,500	68,666	6.7

Switzerland, and the UK. Using the 1:5 ratio with an estimated 300,000 plants yields 1.5 million species of fungi. Others have used similar ratio data or have examined host/substrate specificity to arrive at high species diversity for fungi (Table 1).

May (1991, 1994, 2000) and others have questioned the validity of this estimate because it is unclear that data from Finland, Switzerland, and the UK can be extrapolated to make a global diversity estimate for fungi. While the most complete and accurate species lists for most groups of fungi are from North America and Western Europe, these two regions have relatively low plant species diversity and low levels of endemism for flowering plants (Table 3).

Critics point out that the ratio estimate depends on two assumptions. If either of these two assumptions is false, then the ratio estimate is unreliable.

1. The ratio of fungal to plant species does not change when examined at broader spatial scales.
2. The ratio of fungal to plant species is constant regardless of the diversity of the plant community.

For these two assumptions to prove true the following are necessary:

1. Fungal species diversity and plant species diversity must be positively correlated over a wide range of scales.
2. Fungal and plant species must have similar average range sizes.

Table 3 Current estimates of global plant diversity and levels of endemism

Region	Species diversity	Percent endemic
North America	20,000	21
Central America	30,000–35,000	50
Tropical South America	70,000	78
Temperate South America[a]	6,000–7,000	NA
Europe	12,500	20
Africa	40,000–60,000	60–88
Temperate Asia	45,000	41
Tropical Asia	42,000–50,000	80–95
Austral Asia	16,000	90

Data are from Plant Talk on line, The Diversity of the Plant Kingdom (http://www.plant-talk.org/Pages/Pfacts5.html–http://www.plant-talk.org/Pages/Pfacts9.html)

[a] http://www.biodiversityhotspots.org/xp/Hotspots/chilean_forests/biodiversity.xml

Thus, data on biogeographic distributions, levels of endemism, and host specificity must be taken into account when developing estimates of global fungal diversity.

The following set of papers attempts to develop a rigorous minimum estimate of global fungal diversity based on a critical assessment of current species lists and informed predictions of missing data and levels of endemism. As such, these papers represent both a meta-analysis of current data and a gap assessment to indicate where future research efforts should be concentrated. This estimate will serve as a minimum estimate that can be updated upwards as more information on fungal diversity and distributions are generated.

The fungi covered in the following five papers were chosen to cover major ecological groups: macrofungi, microfungi on plant material, lichenized fungi, aquatic fungi, and soil-inhabiting fungi. These groups include both relatively well known and poorly known but highly diverse taxa. The sixth paper in this series uses the data reported in each of these papers, plus published and unpublished data on arthropod-associated fungi that were presented during a symposium on this subject at the 7th International Mycological Congress (Weir et al. 2002), to develop a conservative, minimum estimate for global fungal species diversity. The last paper in this issue, Piepenbring 2006, serves as an additional indication of our lack of information on fungal diversity from tropical countries.

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