



REVIEW

New scientific discoveries: Plants and fungi

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Societal Impact Statement

Research and publication of the planet's remaining plant and fungal species as yet unknown to science is essential if we are to address the United Nations Sustainable Development Goal (SDG) 15 "Life on Land" which includes the protection of terrestrial ecosystems and halting of biodiversity loss. If species are not known to science, they cannot be assessed on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species and so the possibility to protect them from extinction is reduced. Furthermore, until species are known to science they cannot be fully scientifically evaluated for their potential as new foods, medicines, and products which would help address SDGs 1,2,3, and 8.

Summary

Scientific discovery, including naming new taxa, is important because without a scientific name, a species is invisible to science and the possibilities of researching its ecology, applications and threats, and conserving it, are greatly reduced. We review

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new scientific discoveries in the plant and fungal kingdoms, based largely on new names of taxa published in 2019 and indexed in the International Plant Names Index and Index Fungorum. Numbers of new species in both kingdoms were similar with 1942 new species of plant published and 1882 species of fungi. However, while >50% of plant species have likely been discovered, >90% of fungi remain unknown. This gulf likely explains the greater number of higher order taxa for fungi published in 2019: three classes, 18 orders, 48 families and 214 genera versus one new family and 87 new genera for plants. We compare the kingdoms in terms of rates of scientific discovery, globally and in different taxonomic groups and geographic areas, and with regard to the use of DNA in discovery. We review species new to science, especially those of interest to humanity as new products, and also by life-form. We consider where future such discoveries can be expected. We recommend an urgent increase in investment in scientific discovery of plant and fungal species, while they still survive. Priorities include more investment in training taxonomists, in building and equipping collections-based research centers for them, especially in species-rich, income-poor countries where the bulk of species as yet unknown to science are thought to occur.

KEYWORDS

DNA versus morphology, extinction before scientific discovery, properties of new species, rates of discovery of plants and fungi

1 | INTRODUCTION

While some species unknown to science are already known to local communities and may have local names, scientific discovery, including scientific naming of new taxa is important because without a scientific name, a species is invisible to the world of science and the possibility of researching its ecology, applications, phylogenetic placement, and threats is greatly reduced. Above all, scientific discovery and naming (henceforth “discovery”) is increasingly important for species conservation because the species which remain to be discovered are often those most likely to be at risk of extinction and giving them a name facilitates synthesis and dissemination of the available information about them, a vital first step in evaluating their extinction risk.

New discoveries in the plant kingdom have been published at rates of c. 2,100 to 2,600 species per year for the past 15 years (Figure 1a, IPNI, 2020, Willis 2017). For 2019, 1942 new species of vascular plants were registered on the International Plant Names Index (IPNI) by 28 February 2020 (Dataset S1). The number of new fungal species catalogued for 2019 by 1 March 2020 on Index Fungorum was 1882 (Index Fungorum, Dataset S2). As indexing of 2019 names from the scientific literature continues, totals for both plant and fungal species are likely to rise by at least tens if not hundreds of species before all 2019 publications have been indexed. The rate of species discovery for fungi has increased from 1,000 to 1,500 per year about 10 years ago, to around 2000 with a peak of over 2,500 species in 2016 (Figure 1b).

The fungal kingdom is significantly less well studied than the plant kingdom. Currently 148,000 species of fungi are recognized (Species Fungorum, 2020), the majority in the phyla Ascomycota and Basidiomycota (BOX 1), but it is estimated that the vast majority, over 90%, of fungal species are currently unknown to science and that the total number is somewhere between 2.2 and 3.8 million (Hawksworth & Lücking, 2017).

In contrast, known land plant species have been estimated to number c. 400,000 of which c. 380,000 are vascular plants, with 370,000 belong to the largest phylum, flowering plants (Angiospermae), although these numbers are debated (Nic Lughadha et al., 2016; Nic Lughadha, Bachman, & Govaerts, 2017) and the recently completed World Checklist of Vascular Plants lists 347,298 accepted species (WCVP, 2020). A decade ago, many plant scientists considered that the vast majority of flowering plants had already been discovered, with just 10%–20% remaining to be described (Joppa, Roberts, Myers, & Pimm, 2011). However, the fairly steady rates of publication of new plant species in the interim suggest otherwise (Figure 1a), as do the experiences of many botanists undertaking fieldwork in the tropics. For example, Corlett (2020) suggests as many as 100,000 more plant species remain to be discovered. Giam et al. (2012) consider that least disturbed tropical forests are centers of undescribed species diversity.

The huge difference in level of knowledge between plant and fungal kingdoms is reflected in descriptions of new phyla. Twelve plant phyla are recognized, depending on taxonomic concepts, and no new phyla have been discovered for decades. In contrast,

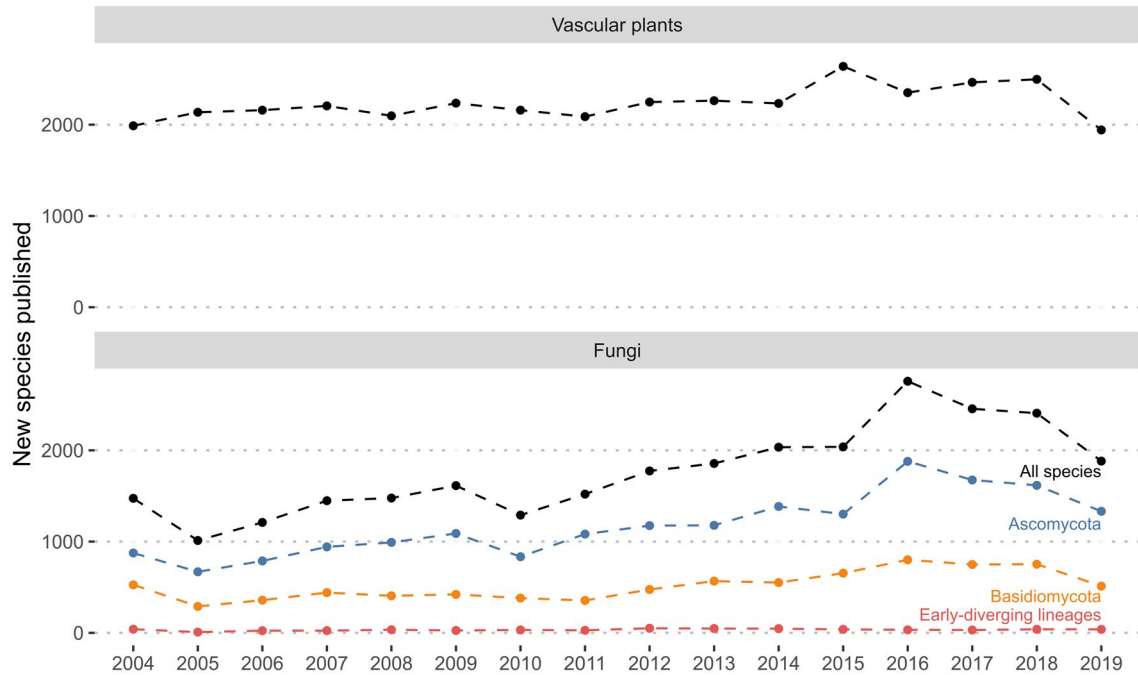


FIGURE 1 Graphs showing number of new species described per annum globally. (a) Number of new plant species described per year. Numbers are quite stable. *Note that scientific literature including some names published in 2019 is still reaching the International Plant Names Index compilers and being indexed, so this number will rise. (b) Number of new fungal species described per year over the past two decades. *Note that names published in 2019 are still being added to Index Fungorum and these numbers will therefore rise

four new phyla of fungi were named in 2018, taking the total to 18 (Tedersoo et al., 2018). While new higher taxa of fungi are now commonly published each year—3 classes, 18 orders, 48 families, and 214 genera in 2019—this is not the case in plants. In 2019 for plants, no new classes or orders, and only one new family (*Wightiaceae* Liu et al., 2019) and 87 new genera were validly published.

There are several reasons why fungi are less well known than plants: They are challenging to study and many of them have cryptic lifestyles spending most of their time as hyphae, or more rarely as cells, e.g. in soil. Characters suitable for morphological classification are fewer than in plants and moreover the characters often overlap and are therefore challenging to use in classification. Also, convergent evolution is common in fungi (Willis, 2018). Finally, the diversity of the Kingdom Fungi is high while the number of mycologists compared to botanists is relatively small.

The increasing rate of fungal discovery in the past two decades is attributed to the advent of DNA studies which have become standard practice, in addition to the traditionally used morphological data, in describing new taxa. This has accelerated the discovery of new species and greatly facilitated the study of relationships. For species-level studies a single DNA marker, ITS (including two spacers ITS1 and ITS2 and the highly conserved 5.8S gene), is in many cases effective across the fungal kingdom for taxonomic purposes although in some groups other markers are needed as well. In contrast, for plants, no single marker is sufficient to distinguish species from each other across the kingdom, or indeed across flowering plants, and most species discoveries today are based solely on morphological data (E. Lucas pers. comm.,

D.Goyder pers. comm., I. Larridon pers. comm.). Most plant species have not been subjected to DNA studies. In fact, comprehensive sampling at generic level is still a target (PAFTOL, 2020). If it were possible to sample and analyse the DNA of plants in the same way as fungi, would species discovery be accelerated as it is for fungi, and would there be the same multiplier effect?

The time from the first collection of a putative new species to its formal description varies greatly. *Barleria deserticola* (Figure 2a), from the Namib coastal desert was first collected 160 years ago, by the explorer Friedrich Welwitsch, but was only re-found in 2009 by US botanist Erin Tripp and named in 2019 (Darbyshire, Tripp, & Chase, 2019). In contrast, the description and publication of *Inversodicraea koukoutamba* (Podostemaceae) collected from a waterfall in Guinea in 2018 took only one year from the first collection (Cheek, Molmou, Jennings, Magassouba, & van der Burgt, 2019). Delays in publication can reflect a lack of availability of specialist taxonomists with the capacity or time to write and publish a formal paper describing new species. They can also result from a former convention, in which naming a species from only a single specimen, showing a single phase of the species' life cycle, was considered poor science (Cheek & Bridson, 2019). This convention contributed to the delay in publishing *Vepris bali*, a cloud forest tree of Cameroon collected 70 years ago. Although taxonomic capacity remains a constraint, aversion to describing species based on a single collection has now been largely overcome, with good reason: new collections may never become available. *Vepris bali*, for example, is presumed extinct (Cheek, Gosline, & Onana, 2018). Publication

BOX 1 Top taxono**Plants**

The five plant families in which most new species were published in 2019 (see list below), include four of those with the largest number of species already documented (see center). However, new species of Orchidaceae, second largest family in terms of known species, greatly exceed those in the largest, Compositae (Asteraceae). This could suggest that orchids were previously under-researched, or simply that orchid taxonomists (including citizen scientists) outnumber Compositae taxonomists. That numbers of active taxonomists influence rate of description of new species is illustrated by the relatively small family Araceae, in the top five rank for new species for the third time since 2014; an alliance of S. American aroid scientists published several papers describing new species (e.g., Croat, Teisher, Hannon, & Kostelac, 2019). The coffee family Rubiaceae, in the top five for new species 2014–2018, ranks second in 2019 marking the culmination of a decade-long revision of West-Central African members of giant pantropical, genus *Psychotria*. Lachenaud (2019) recognised 87 new species, making *Psychotria* 2019's top genus for new species.

The five plant families with most new species published in 2019 (IPNI, 2020).

Family	Numbers of new species published in 2019
Orchidaceae	288
Rubiaceae	157
Compositae (Asteraceae)	100
Araceae	78
Leguminosae	71

The top five vascular plant families in terms of numbers of accepted species (WCVP, 2020).

Family	Global totals species (rounded to nearest 1,000)
Compositae (Asteraceae)	32,000
Orchidaceae	30,000
Leguminosae (Fabaceae)	22,000
Rubiaceae	14,000
Gramineae (Poaceae)	12,000

Fungi

The three orders of fungi with most new species described in 2019 are in decreasing order: Hypocreales, Pleosporales and Agaricales (see list below). These orders dominated also in 2017 (Willis, 2018). Pleosporales and Agaricales are the most species-rich orders of their classes. Hypocreales comprises 200 genera including the genus *Fusarium* in the family Nectriaceae, the top genus and family for new species in 2019 (49 and 113 new species, respectively). Notably, in both 2017 and 2019 four out of five top orders with new species are Ascomycota, the most species-rich phylum of fungi.

The five fungi orders with most new species published in 2019 (Index Fungorum, 2020) and 2017 (Index Fungorum, 2018).

Order	No. spp 2019	Order	No. spp 2017
Hypocreales (Ascomycota)	199	Agaricales (Basidiomycota)	381
Pleosporales (Ascomycota)	198	Pleosporales (Ascomycota)	293
Agaricales (Basidiomycota)	141	Hypocreales (Ascomycota)	129
Lecanorales (Ascomycota)	82	Diaporthales (Ascomycota)	91
Capnodiales (Ascomycota)	81	Eurotiales (Ascomycota)	71



FIGURE 2 New species of flowering plants published in 2019. (a) *Barleria deserticola* (Acanthaceae) published in 2019 but first collected 160 years ago in Angola. Photo: Erin Tripp; (b) *Galanthus bursanus* (Amaryllidaceae) from Turkey, discovered on Facebook. Photo: D.Zubkov; (c) *Gladiolus mariae* (Iridaceae) from Guinea-Conakry. Photo: van der Burgt; and (d) *Begonia rheophytica* (Begoniaceae) from Myanmar. Photo: Kate Armstrong

attracts interest and encourages others to seek new material in the field, sometimes resulting in rediscovery of species hitherto considered extinct (Humphreys, Govaerts, Ficinski, Nic Lughadha, & Vorontsova, 2019).

In fungi, confusion about the identity of the already published species hinders progress. In many groups, the type specimens of all published species need to be studied first, or neo- or epitypes designated for old names, before new names can be published for species. In addition, many new species are discovered from environmental specimens (usually soil samples) but, according to the current rules of nomenclature for fungi they cannot be named because of a lack of a physical voucher specimen which needs to be deposited in a fungarium (Lücking & Hawksworth, 2018; See BOX 2 for more on naming conventions). The debate is also still ongoing as to whether a short DNA sequence is sufficiently robust evidence to justify the publication of a new species name (Zamora et al., 2018), especially as thousands of well-known names still lack DNA barcodes (Schoch et al., 2014). Currently, two Special-purpose committees are exploring the use of DNA sequences as

types, and this topic is due to be further discussed during the next International Mycological Congress in 2022 (May, 2018) and in the International Botanical Congress in 2023 (Turland, Wiersema, Monro, Deng, & Zhang, 2017).

2 | WHERE HAVE THE NEW SPECIES BEEN FOUND?

The top three source countries for the discovery of new plant species have, until recently, remained the same since the 1990s: China, Australia and Brazil, with Brazil generally leading since 2008, publishing 200 or more new species annually (about 10% of total global plant discoveries) (Table 1). However, in 2019, Australia (86 new species) was displaced from its top three position by Colombia (121 new species) and Ecuador (91 new species), and was nearly overtaken by Vietnam (82 new species). The dominance of China, Brazil and Australia is probably attributable to the common factors that

BOX 2 Naming new taxa

The starting point for scientific names for plants and fungi is Linnaeus's *Species Plantarum* (Linnaeus, 1753), which pioneered the binomial standard still used today. Names of taxa at that time were usually descriptive or geographic and in Latin, as in “grandifolia,” meaning “big-leaved,” or “taprobanus” meaning “from Taprobane.” This approach is still popular e.g. *Humicola quadrangulata* (referring to the quadrangular ascospores of this fungus), *Neosetophoma salicis* (growing on *Salix*) and *Turquoiseomyces eucalypti* (referencing the characteristic green-blue discolouration of the host tissue surrounding conidiomata on *Eucalyptus* leaves). However, as numbers of species in genera increased, selecting appropriate descriptive epithets or names not already in use became more challenging. Thus it became common to commemorate specimen collectors (rarely credited otherwise) or famous people worthy of being honoured by a plant or fungus name, David Attenborough and Oprah Winfrey were immortalized in the names of the lichen species *Malmidea attenboroughii* and *Hypotrachyna oprah* (Guzow-Krzemińska et al., 2019; Lendemer & Allen, 2019, respectively). Annabelle Daniel who works tirelessly with local communities to establish Women's Community Shelters across New South Wales, Australia, was recognized when naming the fungal genus *Annabella* (Fryar, Haelewaters, & Catcheside, 2019). Fieldwork sponsors are sometimes credited, such as the UK Government's Darwin Initiative, supporting biodiversity conservation including inventory since 1992 (*Psychotria darwinii*, Cheek et al., 2008). Other options abound, including reflecting the species' history in the epithet (e.g., *Tarenna agnata* Cheek, Poveda, & Molmou, 2015) for a long-overlooked species. However, scientific etiquette discourages naming a new species after oneself.

Examples of people or initiatives honoured in the naming of fungi or plants (a) Oprah Winfrey, after whom lichen *Hypotrachyna oprah* was named; (b) logo of the Darwin Initiative whose support for biodiversity conservation was recognized in the name *Psychotria darwinii*, a shrub; (c) David Attenborough whose environmental work was recognised in the name of the lichen *Malmidea attenboroughii*; and (d) Annabelle Daniel, CEO of Women's Community Shelters, whose work was recognised in the name of the fungal genus *Annabella*. Acknowledgements for images: (a) Oprah Winfrey, photo: <https://www.flickr.com/photos/aphrodite-in-nyc/CCBY> (<https://creativecommons.org/licenses/by/2.0/>); (b) Darwin Initiative, DEFRA, U.K. Government; (c) David Attenborough, photo: Department of Foreign Affairs and Trade website – www.dfat.gov.au, Government of Australia; and (d) Annabelle Daniel, photo: Women's Community Shelters.

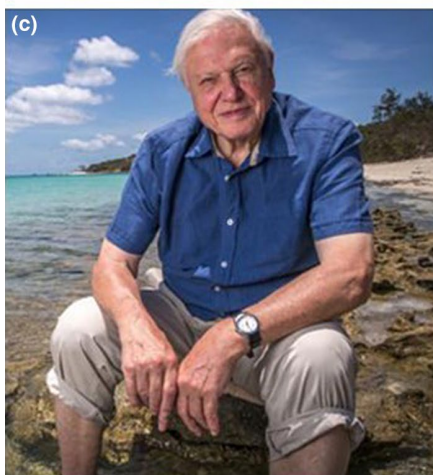
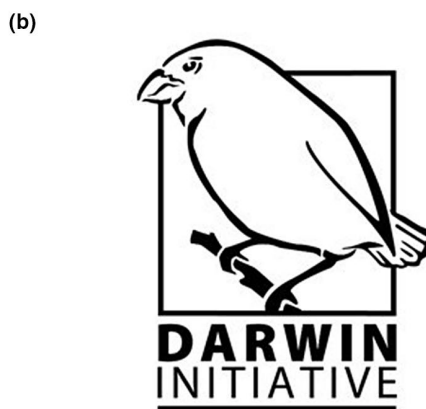


TABLE 1 Top ten countries from which most new species were described in 2019, with numbers of new species published

Plants	Fungi
Brazil 216	China 377
China 195	Thailand 129
Colombia 121	United States 105
Ecuador 91	Australia 96
Australia 86	Brazil 85
Vietnam 82	Spain 75
India 80	Italy 63
Mexico 72	South Africa 62
Peru 68	India 61
Turkey 59	Germany 47

all are extremely large, biodiverse countries which are relatively politically stable and have comparatively large numbers of well-resourced, well-trained professional taxonomists engaged in active Flora (botanical inventory) programmes, respectively, the Pan-Himalayan Flora, the Flora do Brasil and the Flora of Australia. The Flora do Brasil is due to be concluded in 2020 (Filardi, Leitman, & Forzza, 2019), and it will be interesting to see whether rates of publication of new species change following completion. In any case, in terms of continents, Asia and South America are likely to yield greatest numbers of new plant species for the foreseeable future.

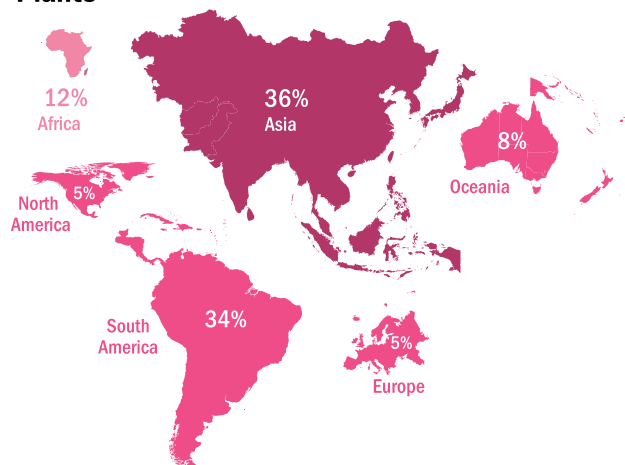
Areas such as the islands of New Guinea and Borneo, also highly biodiverse, much less well explored and collected, saw relatively few new species published in 2019, with 44 and 33 new species of plants, respectively. They lack dynamic Flora programmes such as

that of Brazil, and also lack the enviable scientific capacity of the top three countries. Even less fortunate is Democratic Republic of Congo (DRC), tropical Africa's largest country and home to most of Africa's evergreen forest, together with many other species-diverse habitats. Only seven new species from DRC were published in 2019, reflecting the lack of taxonomists, scientific infrastructure and security, and the periodic negative effects of hazards such as Ebola. In contrast, Cameroon and Gabon, geographically smaller but with more taxonomic activity, are the top countries in tropical Africa for new species description in 2019 (38 and 37 new species, respectively).

Very few new plant species are now newly described from northern temperate or boreal countries, because their flora has generally been well surveyed for many years, and is much less diverse than tropical floras. Exceptions include the four new species of poppy (*Papaver*) discovered in 2019 from Alaska, British Columbia and Siberia (Björk, 2019). Other exceptions are the "micro-species" of temperate genera which reproduce with asexual seeds (that is, apomictically, as clones of stabilized hybrids). Four new agamosperous micro-species of *Taraxacum* (Compositae, the most species rich family of vascular plants BOX 1) were published from the UK in 2019 (Richards, 2019). The UK has not seen publication of a full, sexual, indigenous species for many years.

In complete contrast, new species of fungi are still found almost everywhere: from the tropics to alpine areas, from Europe to Antarctica (Figure 3). On a continental scale, most species of fungi were described from Asia (41%) and Europe (23%) following the pattern of new species published in 2017 (Niskanen, 2018). This is largely due to the fact that the economies of countries in Asia have improved and thus can support such research, and the strong taxonomic tradition

Plants



Fungi

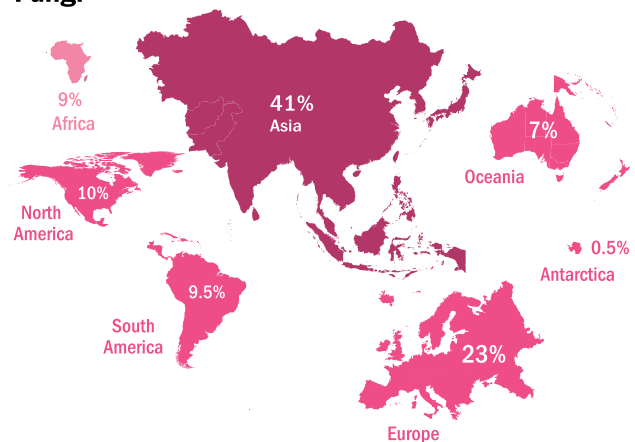


FIGURE 3 Graphic maps of the world's continents showing uneven distribution of newly described species of plants (left) and fungi (right). The size of each continent is proportional to the global percentage of new species published from there and mainly reflects 1) quantity of taxonomic expertise and 2) presence of undescribed species in those areas. For publication of new plant species, Asia and S. America lead the world, led by China and Brazil respectively. Both have comparatively large numbers of taxonomists and undescribed species. Europe ranks third because, as in the case of N. America, although taxonomic activity is comparatively high, a high proportion of plant species present in Europe have already been described. Africa ranks very low, not due to lack of undescribed species but due to lack of taxonomic investment. For new fungal species, which are ubiquitous and vast in number, the map reflects the location of most research activity and taxonomic expertise. Artwork Creative Services/ RBG Kew

in Europe. Seven to ten percent of new species were described from other continents (totaling 35.5%) and 0.5% from Antarctica.

The areas with most new fungal discoveries are not necessarily the least studied historically nor the most diverse ones but are mainly those with most researchers and research activity. For example, although Asia is leading in new species descriptions, not all countries within the continent are equally represented. The vast majority of new species described in 2019 are from China (377 species) and Thailand (129 species, Table 1), whereas data on the fungi from Central Asia are limited and other vast areas, i.e. Indonesia, Malaysia, and Myanmar, show little progress. The leading countries in the description of new species in 2019 are mainly the same as in 2017, when the top three countries were China, Thailand, and Australia (Niskanen et al., in Willis, 2018:18–23).

3 | NEW PLANTS PUBLISHED IN 2019

Here we review the highlights of new plants published in 2019, with a particular focus on plants of potential economic importance, grouped by their potential properties which have still to be evaluated (for a complementary overview of the new plant discoveries by taxonomic family see BOX 1). The importance and potential for humanity of plant and fungal species was recently highlighted (Antonelli, Smith, & Simmonds, 2019). See also in this Special Issue, Howes et al. (2020). For full names and literature citations for all the species and publications mentioned see Dataset S1.

3.1 | Food and drink

Six new species of *Allium*, the genus that gives us garlic, onions, shallots, leeks and chives were discovered in Turkey (Ekşi & Yildirim, 2019), Albania, Greece and China, and two new subspecies of carrot, *Daucus carota*, from Corsica. *Manihot reflexifolia* (Santos et al., 2019) and *M. montana*, were discovered in Brazil. These are new wild relatives of the major root tuber crop *Manihot esculenta*, manioc or cassava, that feeds millions of people in the tropics. Similarly, new wild relatives of the genera that give us yams (*Dioscorea*) and sweet potatoes (*Ipomoea*) were also published from Brazil. Ten new species of spinach-relatives *Chenopodium* have been discovered in California. This genus provides ancient cereals and oil crops as well as leaf vegetables. Thirty new species of *Camellia*, the genus that gives us tea (*Camellia sinensis*) and also ornamental flowering shrubs, were discovered in China and Indo-China.

3.2 | Fodder crops

Numerous new species of plant groups used as food for farm animals were published in 2019, predominantly grasses and legumes. Among the legumes were a new species of vetch *Vicia brulloi* from Sicily (Sciandrello, Del Galdo, Salmeri, & Minissale, 2019), a new grasspea *Lathyrus cirpicii*

from Turkey (Güneş, 2019), and a new sainfoin, *Onobrychis garinensis* and a new sweetvetch *Hedysarum alamutense* (Nafisi, Kazempour-osaloo, Mozaffarian, & Amini-rad, 2019), both from Iran. New grasses include three new fescues (*Festuca*) from Spain.

3.3 | Plants providing medicinal and high value compounds

Several species of the genus *Saussurea* are used in traditional Chinese medicine to treat rheumatoid arthritis and other ailments. The newly discovered *Saussurea balangshanensis* from SW China may also have medicinal potential (Zhang, Tang, Huang, Sun, Ma, & Sun, 2019). *Aloe allochroa* from Kenya and *A. sanguinalis* from Somalia were discovered in 2019. Several species of *Aloe*, most famously *Aloe vera*, are widely used for their pharmaceutical value. *Eryngium arenosum*, from a genus that provides several medicinal plants with anti-inflammatory properties and treatments for high blood sugar and scorpion stings, was discovered in Texas, USA.

Many of the hundreds of species of the genus *Croton* that occur through the tropics are used medicinally to treat a wide range of ailments. Their bio-active compounds include diterpenes, essential oils, anthocyanidins and alkaloids, among which are those with anti-cancer, anti-viral, and anti-bacterial properties. Three new species of *Croton* with potential medicinal properties were published from Brazil (e.g., De Farias, Medeiros, & Riina, 2019), and three species of *Oenothera* (evening primrose, known for production of gamma linoleic acids used to treat systemic sclerosis, eczema, and psoriasis), were discovered in Italy, Poland and a Mexican Pacific island.

Artemisia baxoiensis was discovered in Tibet (Jiao et al., 2019). Artemisinin is the key active ingredient effective against the otherwise drug-resistant malarial plasmodium (Abad, Bedoya, Apaza, & Bermejo, 2012). At least 25 species of the genus *Artemisia* are used medicinally, for a wide range of treatments including anti-bacterial and anti-malarial.

Certain plants are well-known for their production of compounds that are mind-altering stimulants affecting the brain, some of which have medical applications. Among these are certain species of *Virola* in the nutmeg family (Myristicaceae) used for their resinous, tryptamine-containing inner bark from which a snuff is prepared by traditional societies. Six new species of *Virola* have been described, mainly from Costa Rica and Panama (Santamaría-Aguilar, Aguilar, & Lagomarsino, 2019), as well as a new species of *Erythroxylum*, the genus best known for cocaine, *E. niziae* from Brazil (Loiola & Cordeiro, 2020).

Plants also produce natural, non-persistent pesticides of value to the organic food industry such as rotenoids from the legume genus *Lonchocarpus*, two new species of which were recently discovered in Mexico. Species of the neotropical genus *Tagetes* of the daisy family Compositae or Asteraceae produce essential oils with at least 30 compounds showing bioactivity, of value in preserving food, as cheap, effective, and human-friendly pesticides, but also as anti-fungal and anti-bactericidal compounds. *Tagetes imbricata* was newly discovered in Argentina (Schiavinato & Bartoli, 2019).

3.4 | Timber and crafts

Among the new species of timber tree were a *Chlorocardium* (green-heart) and *Cedrela domatifolia* (mahogany family) the latter (Palacios, Santiana, & Iglesias, 2019) from a genus used for making traditional cigar boxes. Trees of potential agro-forestry interest are: *Eucalyptus dalveenica*, *Acacia ammitia* and *Inga kurserii*. Eight new species of *Calamus*, a palm genus key in providing rattan for cane furniture, still wild-harvested, were discovered in SE Asia and India (Mondal, Basu, & Chowdhury, 2019). More than 20 new bamboo species were discovered including five new *Chusquea* species from Brazil and Peru, and nine species of *Dinorchloa* from SE Asia, principally Indonesia, also new species of *Dendrocalamus*, *Phyllostachys*, *Fimbribambusa*, and *Yushania* (from Yunnan, China; Zhang, Ye, Liu, & Li, 2019), were published.

3.5 | Herbs and Spices

Three new species of *Zingiber*, the genus that produces ginger (*Zingiber officinale*), were described from the Philippines (Docot et al., 2019) and Vietnam, and five new species of *Curcuma*, best known for turmeric (*Curcuma longa*), were found in China and Indo-China. *Piper cavanoense*, from the genus that gives us black pepper (*Piper nigrum*), was published from Colombia, and four species of *Vanilla* from Cuba (Calvo, Esperon, & Saulea, 2019) and central and S. America. Two new species of cinnamon (*Cinnamomum*) were found in Vietnam and Ecuador, while seven new species of the genus *Syzygium*, best known for cloves, were found in India, New Guinea and the west Pacific. Meanwhile, *Ocimum sebrabergensis* a new species of basil, was discovered in Namibia, four new species of *Salvia* (sage) from Mexico and China, and *Lavandula nooruddinii* a new lavender from Oman (Patzelt & Hinaï, 2019).

3.6 | Horticulture

New discoveries of temperate garden groups continue to be made, especially from Turkey, China and adjoining countries. Bulbous or cormous ornamental plants include species of the genera *Crocus*, *Iris*, *Fritillaria*, *Gagea*, *Lilium*, *Tulipa*, *Galanthus* (discovered on Facebook; Zubov, Konca, & Davis, 2019, Figure 2b) and *Muscari*. The spectacular red-flowered *Gladiolus mariae* was found on a sandstone table-top mountain in Guinea, West Africa (van der Burgt, Konomou, Haba, & Magassouba, 2019, Figure 2c). Temperate and alpine herbaceous and climbing plants published in 2019 include *Aconitum*, *Aster saxicola*, *Geranium socalteum*, *Campanula cremnophila*, *Kniphofia vandeweghei*, *Meconopsis brachyneura*, two *Clematis* species, six species of *Ranunculus*, and species of *Alchemilla*, *Trollius*, *Dianthus*, *Primula*, *Lysimachia*, *Anemone* and *Oxalis*. New species of temperate ornamental shrubs and trees were described in the genera *Rhododendron*, *Magnolia*, *Escallonia*,

Crataegus, *Cornus*, as well as a *Ceanothus* from Mexico, and two *Cotoneaster* species from Iran.

Species discovered from tropical areas which have potential interest as garden ornamentals or house plants are: three spectacular-flowered *Hibiscus* from Fiji, *Spathiphyllum globulispadix* (a "peace-lily"), *Hoya tengchangensis*, *Maranta sophiana*, *Peperomia aggregata*, *Pelargonium sessiliflorum*, *Jasminum honghoense*, *Prostranthera crocodyloides*, and species of *Sinningia*, *Cyrtandra*, *Petrocosmea*, *Chlorophytum* and *Aspidistra*. Twenty-eight new species of tree ferns were published in 2019, mainly *Alsophila* from New Guinea and *Cyathea* from Venezuela and Colombia. Forty-five new species of *Begonia* were also published (BOX 3), mainly from SE Asia, including the remarkable *B. rheophytica* (Figure 2d), which grows in fast-flowing water (Hughes, Aung, & Armstrong, 2019).

Among the new succulent species for 2019 are *Echeveria vulcanicola* from a volcano in Peru, *Agave oteroi*, *Sedum ichangensis*, and 20 new species of cacti (Cactaceae), many from Argentina, including *Tephrocactus abditus* (Janeba & Ferguson, 2019).

4 | NEW FUNGI PUBLISHED IN 2019

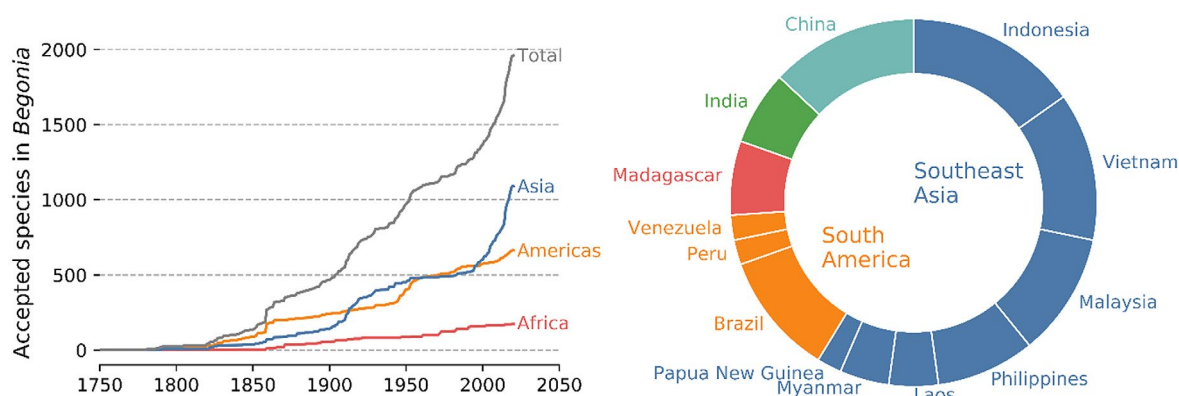
Here we review the highlights of new fungi published in 2019, grouped by their life-form and properties. For full names and literature citations for all the species and publications mentioned see Dataset S2.

4.1 | Mycorrhizal fungi

Of the 1,882 species described in 2019, about 200 species were from evolutionary groups known to form beneficial mycorrhizal associations with plants. Mycorrhizal fungi have co-evolved and diversified with their plant partners and are among the most speciose groups of fungi on the planet. The first land plants already had mycorrhizal relationships and today around 90% of all land plant species engage in mutualistic relationships with fungi.

Fifty-one new species were described from the family containing the milkcaps (*Lactarius* and *Lactifluus* (e.g., Delgat et al., 2019, Wang et al., 2019)) and the brittlecaps (*Russula* (e.g., Adamčík et al., 2019)), an enigmatic group of over 2,000 species of mushrooms that form mycorrhizal associations with vascular plants ranging from giant *Lithocarpus* trees in southeast Asia to dwarf willows (*Salix arctica*) in the Arctic. Another group that saw a surge in new species descriptions were the boletes (Boletaceae): 37 new species described across 15 genera (e.g., Vadthanarat et al., 2019; Zhang, Li, Wang, & Zeng, 2019). Of particular note are the latest results from a long-term, ongoing study of the colloquial "Old Man in the Woods" bolete (*Strobilomyces*) which introduced eight new species to this genus (Han et al., 2019).

Truffle-like species that have independently evolved in multiple groups were also well-represented, including new species from the

BOX 3 New discoveries of *Begonia*

The genus *Begonia* occurs throughout the tropics, mainly as narrowly endemic terrestrial herbs of undisturbed cloud and montane forests. Some are epiphytes or climbers, and others are restricted to shady rock faces or waterfalls.

On average, 60 new *Begonia* species per year were published 2014–2019, making it one of the fastest growing genera in terms of known species.

Forty-six new *Begonia* species were described in 2019 mainly from SE Asia, China, Indo-China and South America (see Pie Chart above right).

Note this analysis is based on Hughes et al. (2015–Present) data which was more up to date than IPNI at the time of writing.

Most (73%) of the new *Begonia* species published in 2019 were based on type specimens collected in the preceding five years. This likely reflects new exploration which has revealed previously undocumented narrow geographic endemics. However, in some cases the earliest collection can predate the specimen selected as type by a decade or more reflecting the difficulty of working on older herbarium material.

The total number of accepted species is 1963 (as of March 2020) and is expected to exceed 2000 species by the end of 2020 (see above left). Several hundred further new *Begonia* species potentially remain to be found, with species new to science considered highly likely to be found in Borneo and New Guinea.

basidiomycete genera *Russula* (Vidal et al., 2019) and *Cortinarius* (Pastor et al., 2019) as well as ascomycetes such as *Ruhlandiella* (Kraisitudomsook et al., 2019), a truffle-like cup fungus, and the true-truffles, *Tuber* (Leonardi, Paz-Conde, Guevara, Salvi, & Pacioni, 2019). These species have lost the ability to forcefully eject their spores, relying on insects, birds, and small mammals for dispersal.

Ongoing research in Madagascar continues to reveal novel species such as *Cantharellus bruneopallidus*, which is associated with at-risk hosts and *Intsia bijuga*, a vulnerable tree species facing possible global extinction due to illegal logging (Hyde et al., 2019).

Arbuscular mycorrhizae (AM) from the phylum Glomeromycota are essential mutualists of about 90% of all plant species, yet they lack complex spore-bearing structures and are typically found as hyphae within roots or as large, colorful spores in soil. Recent discoveries in AM fungi include species from extreme environments such as exposed, rocky hills on the African savannah and Polish coal mine spoil heaps, where these species can endure an almost complete lack of nutrients and temperatures exceeding 50°C (Błaszowski et al., 2019, Figure 4a).

4.2 | New plant pathogenic fungi

Many new plant pathogenic fungi associated with plant diseases of economically important plants were discovered in 2019, predominantly from the phylum Ascomycota (Figure 4).

Notably, one of the *Fusarium oxysporum* strains (formerly known as Tropical race 4) responsible for Panama disease of banana (*Musa*), that threatens the productivity of one of the most popular cultivars, Cavendish, was recognized as the new species *Fusarium odoratissimum*. In addition, eight further members of this complex were described as distinct novel species (Maryani et al., 2019). Also, six new pathogens of grape (*Vitis vinifera*) were described (Aigoun-Mouhous et al., 2019; Berlanas et al., 2020; Lesuthu et al., 2019; Lorenzini, Cappello, Perrone, Logrieco, & Zapparoli, 2019; Wang et al., 2018).

Other new pathogenic fungi included *Colletotrichum shiso*, an anthracnose pathogen of perilla (*Perilla frutescens*), a source of seed oil in China, Japan, India, Thailand, and Korea (Gan et al., 2019);

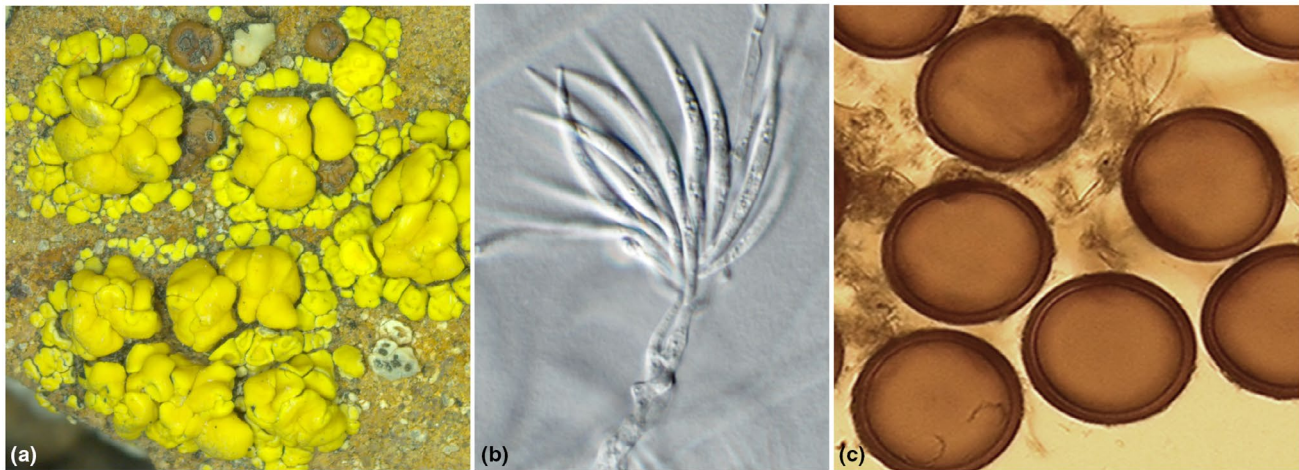


FIGURE 4 Three new species of fungi published in 2019. (a) *Lecanora solaris* (Lecanorales, Ascomycota), Altai Mountains, Russia. The name “solaris” refers to the bright yellow “sunny” colour of the lichen; (b) *Falcocladium eucalypti* (Falcocladales, Ascomycota), a weak foliar pathogen of *Eucalyptus*, known from South Africa and Australia, suggesting that this fungus could have been introduced to South Africa along with its host; and (c) *Rhizoglossus dalpeae* (Glomeromycota), glomerospores of an arbuscular mycorrhizal fungus that was found from an inselberg located within savanna zone in Benin, where the temperature during a 5-month drought ranges from 40° to 60°C. Photos: (a) E. A. Davydov; (b) P.Crous; (c) J. Błaszowski

Ceratocystis destructans, a canker-causing pathogen of almond (Holland et al., 2019), and *Dwiroopa punicae*, which causes leaf spotting and fruit rot in pomegranate (*Punica granatum*) (Xavier, 2019). In this latter study, the new family Dwiroopaceae was also proposed to accommodate this genus.

Pathogens of important non-food plants were also discovered, such as *Cytospora elaeagni* associated with canker disease of *Elaeagnus angustifolia* a plant used to combat desertification in China (Zhang, Alvarez, Bonthond, Tian, & Fan, 2019), and two new fungal species causing leaf spots and dollar spots on amenity turf-grasses (Hu et al., 2019; Liang, Li, Zhao, & Cai, 2019).

New parasitic species published in the Basidiomycota include the rust *Quasipucciniastrum agrimoniae*, a biotrophic parasite of agrimony (*Agrimonia*), a plant used in traditional medicines (Qi, Cai, & Zhao, 2019) and *Neopuccinia bursa* from *Protium heptaphyllum* in Brazil, a tree of local importance as a source of resin, food, medicine, and wood (Martins, Sakuragui, Hennen, & Carvalho, 2019). A new smut, *Moesziomyces kimberleyensis*, was found on inflorescences of *Echinochloa kimberleyensis*, an endemic Australian grass of potential conservation concern (Li, Shivas, Li, & Cai, 2019). Six novel yeast-like Exobasidiomycetes in the genera *Entyloma*, *Golubevia*, and *Jamesdicksonia* were discovered causing white haze post-harvest disease on apples (Richter, Yurkov, Boekhout, & Stadler, 2019).

4.3 | New decomposers

Decomposer fungi recycle nutrients from nearly all types of organic material, which can then be used by other organisms. The spore-bearing structures of the decomposers described in 2019 vary enormously in shape and size from conspicuous woodland brackets and mushrooms, such as the delightfully fragrant *Marasmius*

indojasminodorus found on dead wood and leaves in India, to microscopic moulds such as *Mucor orantomantis* discovered in the feces of a praying mantis in South Korea (Phookamsak et al., 2019). Among the mushroom-formers, *Mycena* gained more new members than any other genus. Thirteen new *Mycena* species were described from China and Mexico (Cortés-Pérez et al., 2019; Na & Bau, 2019a, Na & Bau 2019b). Remarkably, all Mexican discoveries represented bioluminescent species, a property duly celebrated in the names of *Mycena fulgoris* (fulgoris; meaning brightness), *M. lumina* (=light), *M. luxfoliicola* (lux = light, foliicola = dwelling on leaves) and *M. nebula* (=a group of stars).

Each year some of the world's mycologically most neglected regions and habitats become hotspots of new species discoveries. Studies yielding some of the more impressive numbers (40 + species each) of new decomposers in 2019 ranged from a major contribution to the checklist of wood-inhabiting poroid Basidiomycota (bracket fungi) in Africa (e.g., Ryvarden, 2019a, 2019b, 2019c), through projects focusing on microscopic Ascomycota from very specific microhabitats. One example of the latter was a study of decaying wild fruits and seed pods found mainly in Thailand that yielded eight new genera and 50 new species (Jayasiri, 2019). Similarly, a study of decaying wood submerged in freshwater in Thailand and China generated 129 fungal cultures representing three new genera and 47 new species (e.g., Luo, 2019).

4.4 | New lichens

Lichen-forming fungi are important colonizers of ecosystems, weathering rocks to release mineral nutrients, capturing nutrients from the air, and are important in food-webs. In 2019, over 200 new species of lichenised fungi were described spanning 37 families and



FIGURE 5 A new animal-associated fungus published in 2019. *Cordyceps jakajanicola* (Hypocreales, Ascomycota), Thailand. (a) Fungus on cicada nymph (sexual morph); and (b) fungus on cicada nymph (asexual morph). The fungus grows inside its host and sprouts its reproductive parts outside the host's body. Many of the species, together with their insect hosts, are used in traditional Chinese medicine. Photos: BIOTEC

87 genera. The genus *Micarea* took first place with 24 new species (e.g., Kantvilas & Coppins, 2019).

The new species were discovered in a range of diverse locations including high altitude tea plantations in Sri Lanka, the Altai Mountains in Russia and various islands such as the Falklands (Malvinas), Galapagos, and Lord Howe (Archer & Elix, 2019; Bungartz & Spielmann, 2019; Fryday, 2019; Weerakoon, Aptroot, Lücking, Arachchige, & Wijesundara, 2019; Yakovchenko, Davydov, Ohmura, & Printzen, 2019; Figure 4c). In two of the most globally threatened tropical biomes—the seasonally dry tropical forests of Mexico and the Atlantic forests in Northeast Brazil—multiple species descriptions were concentrated in the orders Arthoniales and Ostropales (de Lima et al., 2019; de los Ángeles Herrera-Campos et al., 2019).

New discoveries were found on a myriad of substrata, including the bark of iconic old-growth coastal redwood trees in California (*Chaenotheca longispora*; Naeborg et al., 2019). One discovery (*Allographa kamojangensis*) derived unexpectedly from an online user who posted a photo of a lichen to the Facebook group *Lichens Connecting People*, highlighting the increasing relevance of social media and citizen science in modern taxonomy and biodiversity research (Jatnika et al., 2019).

4.5 | New animal-associated fungi

The diversity of fungi is largely unknown and undescribed, and this is no different for the animal-associated fungi. For example, as little as 1.5% of all insect-associated fungi has been described thus far (Mueller & Schmit, 2007). Animal-associated fungi have great potential for biological control of insect pests. *Beauveria*

bassiana is the most widely used biocontrol agent against many major arthropod pests (Garcia-Estrada et al., 2016). Some species, like those of the genus *Cordyceps*, are used in traditional Chinese medicine.

In 2019, animal-associated fungi from different lineages were described including forty-eight new species of animal-associated Sordariomycetes (Figure 5). Among these are eight species of *Ophiocordyceps* from cicada nymphs and termites in Thailand (Crous, Schumacher, et al., 2019; Crous, Wingfield, et al., 2019; Tسانathai et al., 2019) and seven species of ambrosia fungi in the genera *Ambrosiella*, *Toshionella*, and *Wolfgangiella* (Mayers et al., 2019), which are cultivars of ambrosia beetles, depending on the beetles' fungus-carrying organs (mycangia) for dispersal.

Fourteen species of Laboulbeniomycetes that are obligatorily associated with arthropods were described from beetles, cockroaches, termites, flies (including the ectoparasitic bat flies), and true bugs (De Kesel & Haelewaters, 2019; Dogonniuck, Squires, & Weir, 2019; Haelewaters & Pfister, 2019; Haelewaters, Pfliegler, Gorczak, & Pfister, 2019b; Hyde et al., 2019; Song et al., 2019). A recent advance in taxonomic studies of these elusive fungi results from morphometry and molecular phylogeny (e.g., Haelewaters, De Kesel, et al., 2019; Haelewaters, De Kesel, & Pfister, 2018; Sundberg, Kruys, Bergsten, & Ekman, 2018).

Given that mycologists have only observed a fraction of the estimated diversity in the Kingdom Fungi, it is no surprise that the ecological diversity of groups of fungi is also underestimated. Indeed, newly described species often extend known ecological ranges. Of note in 2019 is *Emericellopsis koreana*, isolated from the gut of a mosquito larva in South Korea (Phookamsak et al., 2019). Until the discovery of this species, taxa in *Emericellopsis* had been found from estuarine or

marine habitats associated with seaweed, agricultural substrata, peat, forest soil, and rhizomes (Gonçalves, Vicente, Esteves, & Alves, 2020).

5 | WHERE WILL THE NEXT NEW PLANTS AND FUNGI BE FOUND?

Despite the ongoing loss of natural habitat in the 21st century, new plant species continue to be discovered. In some extreme cases, the numbers of known species in groups considered to be well-known have nearly doubled since 2000. One example is the tropical Asian pitcher plants, *Nepenthes*, long cultivated in plant collections, which when revised in 2001 were considered to have 87 species globally (Cheek & Jebb, 2001). However, fuelled by troops of citizen scientists searching remaining scraps of natural habitat intensively within the SE Asian range of the genus, hoping for and making new discoveries, the number of species has now risen to 181 and is still rising (Murphy et al., 2020). Another genus showing rapid growth, especially in SE Asia is *Begonia* (BOX 3).

Statistical estimation of the quantity and distribution of the plant species still awaiting discovery suggests that they are heavily concentrated in the regions of the world already recognized as biodiversity hotspots (Joppa, Roberts, Myers, et al., 2011). For example, it is highly likely that some new discoveries will continue to be made even in areas that are considered intensively surveyed such as the highly species-diverse Cape of South Africa. This is because, typically, many new species discovered today tend to be highly geographically localized (narrowly restricted endemics), with few sites and minute footprints: more widespread species already tend to have been discovered (Cheek et al., 2018). Such restricted distributions tend to result in these new species being highly likely to be unwittingly threatened by habitat clearance, making their discovery, naming and extinction risk assessment urgent: species lacking IUCN threat status are less likely to be safeguarded than those that have IUCN status (Nic Lughadha et al., 2020). Today, species that are already globally extinct are still being described and published e.g. *Nepenthes extincta* described from a single 1978 collection (Cheek & Jebb, 2013).

However, the greatest number of new plant species and genera yet to be discovered is likely to be from those tropical to warm-temperate areas of the world harboring surviving natural habitat which remains under-surveyed, either spatially, temporally, or both. Large areas of highly biodiverse rainforest and other species-rich habitat remain incompletely surveyed for plants. These can be identified through study of herbarium specimens (digitized or not) and virtual herbaria or data aggregators such as the Global Biodiversity Information Facility (GBIF). Examples of such un-surveyed habitat plainly visible as lacking records on maps produced from GBIF data (Paton, 2020), are large areas in lowland Indonesian New Guinea (Utteridge pers. comm. to Cheek 2020, see also Cámara-Leret et al., 2020), Republic of Congo and neighboring Angola (Goyder et al., 2018; Goyder & Gonçalves, 2019) and large areas of the Amazon forest (Forzza pers. obs.). There

is no doubt that numerous new species will result if and when these areas are botanically surveyed more extensively and the resultant samples are studied by relevant taxonomic specialists, provided that the areas can be sampled before they are cleared for development projects. In fact, we consider it likely that areas not hitherto recognized as biodiversity hotspots may emerge as a result of such fieldwork. One such example is the Bakossi Mts of Cameroon, almost unsampled until 1995, which figured on no maps for biodiversity conservation. Following intensive sampling they were revealed to be one of the top five documented hotspots for plant species diversity (2,412 species) in tropical Africa, including 74 narrowly endemic species that were new to science (Cheek, John, Darbyshire, Onana, & Wild, 2004) and resulted in a new National Park being created for plants. This is in sharp contrast to the view, based on modeling and statistical estimation, that most new species will be found in areas already known to be species diverse (Joppa, Roberts, Myers, et al., 2011).

New fungi will likely be found in the same under-sampled areas as plants, but our knowledge of fungi is so incomplete that new species will also continue to be discovered even in well-studied and densely populated areas such as the Netherlands (e.g., De Kesel & Haelewaters, 2019) and the United Kingdom, which are so well sampled botanically that no new plant species (apart from micro-species and new, stabilized hybrids) are expected there. Indeed, in 2019, at least fifty new species were added to the British mycota (Ainsworth & Henrici, 2020; Clubbe et al., 2020), of which nine were new to science (e.g., Ekanayaka, 2019) with several others published in preliminary findings but not definitively named (e.g., Henrici & Kibby, 2019).

New fungi can be found almost anywhere, from the rocks of Antarctica, to the dung of sheep, the nests of leaf-cutting ants, sand dunes and even in the air of basements (Crous, Schumacher, et al., 2019; Crous, Wingfield, et al., 2019; Hyde et al., 2019; Rodrigues, 2019). They occur in terrestrial habitats but also in water, such as *Annabella australiensis* and *Kamalomycetes mangrovei* growing on decaying wood in mangroves (Fryar et al., 2019; Hyde et al., 2019). Numerous new species of fungi, as well as undescribed higher taxonomic ranks, are also discovered each year from environmental samples (e.g., Tedersoo, Bahram, & Puusepp, 2017). Most of these, however, remain unnamed due to the lack of physical voucher specimens. One of the major challenges in fungal taxonomy is to shed light on these “dark taxa” (Lücking & Hawksworth, 2018; Ryberg & Nilsson, 2018).

6 | CONCLUSION

Research and publication of the planet's remaining undiscovered plant and fungal species is essential if we are to halt biodiversity loss. If species remain unknown to science they cannot be factored into conservation planning and so the possibility to protect them from extinction is reduced. Furthermore, until species are scientifically documented they cannot be fully evaluated for their potential as new foods, medicines, and products for the benefit of humanity

and of the planet. We recommend that more resources are invested in scientific discovery and description of plant and fungal species urgently, while they still survive. Priorities include more investment in training taxonomists, and creating employment and building and equipping collections-based research centers for them, especially in species-rich, income-poor countries where the bulk of species unknown to science are thought to await scientific discovery.

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AUTHOR CONTRIBUTIONS

T.N., M.C., and E.N.L. conceived the paper. P.K., J.C., T.N., B.L., B.D., D.H., E.G., T.L., A.M.A., Y.G., K.H., P.C., H.L., B.E.W., K.M.W., E.N.L., and M.C. contributed to data collection, analysis and/or interpretation. T.N., B.L., B.D., D.H., E.G., T.L., A.M.A., M.C., and M.H. wrote the first draft. T.N., P.K., B.L., B.D., D.H., P.C., R.C.F., E.G., T.L., Y.G., K.H., A.M.A., J.C., E.N.L., and M.C. revised the manuscript.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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