Fungarium

Curated by KATIE SCOTT and ESTER GAYA

BIG PICTURE PRESS
Royal Botanic Gardens Kew

Fungarium

For my mum, Viv – K.S.
To the next generation of mycologists! – E.G.

BIG PICTURE PRESS

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Artwork not to scale

FSC

Welcome to the Museum

ENTER HERE

Fungarium

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B P P

Preface

Fungi are probably the least known and most misunderstood organisms on Earth. More closely related to animals than plants, they are critical to the maintenance of our food supply, health, ecosystems, and global atmospheric chemistry. They also exhibit an amazing variety of lifestyles and forms, from the microscopic to the bizarre.

Fungi impinge on almost all aspects of our lives and are all around us; even as you read this you will be breathing in some microscopic fungal spores from the air. Life would not be as we know it without them. Our forests and crops need them to flourish – without them all dead wood and leaves would never fully decay but accumulate year on year. Our cattle and sheep, along with other ruminant animals, need some in their stomachs to break down the grass they eat. Our shops would be without coffee, tea and chocolate, many cheeses, all alcoholic and many fizzy drinks, biological detergents, soy sauce, vinegar, all kinds of mushrooms and mushroom products, and more. Our lives would also be shorter without antibiotics and other pharmaceutical products from fungi. On the downside, some can grow on and in us, kill our crops and trees, spoil our food, invade our homes or even poison us.

Yet we know barely 5 per cent of the 2.2–3.8 million fungal species on Earth, and previously unknown fungi can be found almost anywhere – even in your own back yard. Species new to science are continually being found not just in remote tropical forests but even in the UK. Their vast extent has only come to light in the last few years from molecular studies. These have revealed that there are staggeringly huge numbers of species that have never been seen – and are known only from their DNA.

Royal Botanic Gardens Kew

Professor David L. Hawksworth CBE
Royal Botanic Gardens, Kew

FUNGARIUM

Entrance

Welcome to Fungarium

Fungi are hardly mentioned in school and even university today; they remain a big unknown for many. We have put together a special museum so you can explore this mysterious kingdom. In these pages, you will see magnified microscopic fungi, get inside animals, climb mountains, and have a glimpse of the underground world inhabited by fungi.

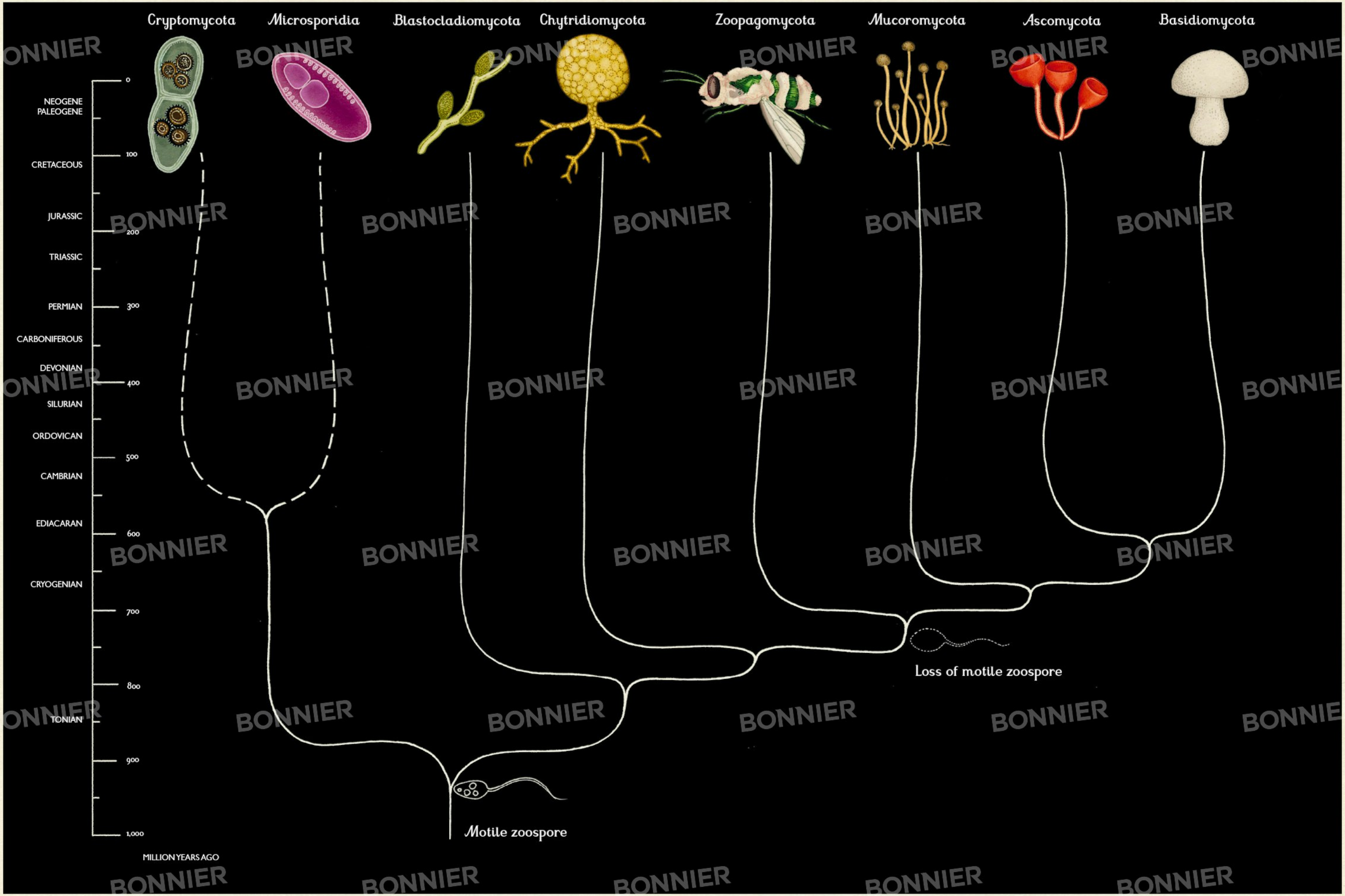
Tour the galleries and learn why fungi are more related to animals than plants. Discover how they evolved. Find out about their amazing variety of shapes and colours, some of them alien-like, almost monstrous, and disgustingly smelly, others incredibly beautiful. The illustrations in this book are not to scale because fungi vary so much in size. Some are microscopic while others are surprisingly large – one *Rigidoporus ulmarius* at Kew Gardens (page 26) had a bracket with a circumference of around 5 metres!

Have you ever heard about the 'zombie fungi' that can take control of insect bodies? And the caterpillar fungi used in Chinese traditional medicine? Discover the most important life-saving drugs that come from fungi; some have revolutionised human transplant surgery. Learn also about fungi that can be eaten and that represent some of the world's best delicacies. There are many more than can be found in western supermarkets! But be cautious and remember some of them may kill you.

Let *Fungarium* introduce you to the underground world of mycorrhizal networks, the key players in all terrestrial ecosystems.

As you travel through *Fungarium*, we are sure you will become as enthralled, fascinated and excited by fungi as we are, as you learn more about their exquisite forms, lifestyles, habitats and importance to us and the world we live in.

Dr Ester Gaya
Royal Botanic Gardens, Kew


Cryptomycota
Microsporidia
Blastocladiomycota
Chytridiomycota
Zoopagomycota
Mucoromycota
Ascomycota
Basidiomycota
0
NEOGENE
PALEOGENE
100
CRETACEOUS
JURASSIC
200
TRIASSIC
PERMIAN
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CARBONIFEROUS
DEVONIAN
400
SILURIAN
ORDOVICAN
500
CAMBRIAN
EDIACARAN
600
CRYOGENIAN
700
800
TONIAN
900
1,000
MILLION YEARS AGO
Loss of motile zoospore
Motile zoospore

The Tree of Life

All species on Earth are related and connect together in a 'tree of life'. Reconstructing this tree allows us to tell the story of evolutionary history. What does the fungal tree of life look like?

It turns out that this is a difficult question to answer. Sometimes similar-looking fungi are not at all closely related, and even more problematically, a large proportion of species are still awaiting discovery, hidden underground, or within the cells of other organisms. Without an accurate idea of the diversity and relationships of the fungi species alive today, it is difficult to build an understanding of historical relationships of the kingdom Fungi.

Identifying similarities and differences in DNA is helping us to understand how the branches of the fungal tree fit together. This includes the discovery of new branches such as the Cryptomycota and Microsporidia, two early groups that were thought not to contain chitin, one of the key features of fungi (page 8). DNA and detailed microscopy studies have proved this wrong. Other groups, including downy mildews (Oomycota) and slime moulds (Myxomycota), have been proved to not belong to Fungi.

The earliest fungi are thought to have evolved around one billion years ago and to have been simple, single-celled organisms that lived in water. They reproduced using motile asexual spores (zoospores) and propelled themselves forward with a whip-like structure called a flagellum. Indeed, modern-day Cryptomycota, Chytridiomycota and Blastocladiomycota share some of these features.

The evolutionary transition from aquatic to land-dwelling fungi is estimated to have taken place around 700 million years ago. The first two groups to evolve in the new environment were the Zoopagomycota and Mucoromycota, which lacked motile spores. Zoopagomycota are almost exclusively pathogens, parasites or commensals (living on or within animals and other fungi without harming them). In contrast, Mucoromycota form associations with plants.

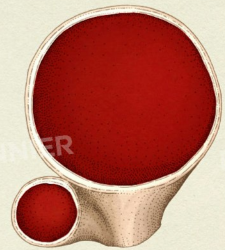
The evolution of the two fungal groups which contain species that can form highly complex spore-bearing structures is considered to have occurred around 600–700 million years ago. These are known as Ascomycota and Basidiomycota. Together they contain the vast majority of known fungal species – around 140,000 in total. They also include the single-celled yeasts, which have arisen in multiple diverse lineages, and other microscopic fungi.

Research on the fungal tree continues and there are still many questions arising from the ever-increasing rate at which species are being discovered. A whole new 'invisible dimension of fungal diversity' in our soils, bodies and waterways is being revealed – the so-called dark taxa. Mycologists are only starting to explore this unknown territory.

FUNGARIUM

Gallery 1

Fungal Biology



What is a Fungus?
Sexual Reproduction
Asexual Reproduction
Spores
Growth
Ecosystem: Mountains

What is a Fungus?

Fungi have a kingdom of their own, like animals and plants do, but theirs is by far the least known. As new species are constantly being discovered, scientists think we have barely scratched the surface and that of the estimated 2.2 to 3.8 million species on Earth, fewer than 5 per cent have been identified.

Historically, fungi were treated as plants and studied by botanists. They were included in *Species Plantarum* by the famous naturalist Linnaeus (also page 48) in 1753. That is why it often comes as a surprise to learn that fungi are more closely related to animals than plants. Just like the outer skeletons of insects and crustaceans, fungal cell walls are made largely of chitin, a substance similar to the keratin of human hair and skin. Plant cell walls contain cellulose instead. Plants manufacture their own food from carbon dioxide in the air, light, and water through a process called photosynthesis. Like animals, fungi can't manufacture their nutrients. Animals ingest their food by engulfing or swallowing it, while fungi secrete enzymes that dissolve food outside their bodies and absorb the nutrients through their cell walls. Another obvious difference is that animals move around to search for food, while fungi grow towards it.

There are at least eight phyla (major groups) of true Fungi, although some researchers recognise up to 18 or more! These phyla include Cryptomycota, Microsporidia, Blastocladiomycota, Chytridiomycota, Zoopagomycota, Mucoromycota, Ascomycota, and Basidiomycota. Some of the most ancient are single-celled and don't look at all like typical fungi. Most familiar fungi belong to Ascomycota and Basidiomycota, which produce septate hyphae (typical fungal filaments) and can include mushrooms, yeasts and those fungi that associate with algae to form lichens.

Key to plate

1: ***Rozella* sp.**
(Cryptomycota)
Motile zoospore
The motile zoospore, with an appendage (flagellum) enabling it to swim, is reminiscent of spermatozoids and reminds us of our close connection to fungi.

2: ***Rhizophydium planktonicum***
(Chytridiomycota)
A fungal parasite of microscopic *Asterionella*, this is a freshwater diatom (single-celled algae). These are ancient fungi that mainly live in water and soil.

3: ***Piromyces communis***
(Chytridiomycota)
Piromyces communis can be found in the rumen and hindgut of herbivores. These fungi produce enzymes that help the animals digest fibres from plant cell walls. Chytrids are generally single-celled with delicate filaments (rhizoids) penetrating host tissues.

4: ***Berwaldia schaefernai***
(Microsporidia)
Spore (sporoblast)
Each spore is surrounded by a vesicle (sac for storage) composed of a thin outer membrane-like sheath and an inner layer of tubular structures (coiled polar tubes). The external layer is made of proteins and chitin. Microsporidians are single-celled parasites of animals.

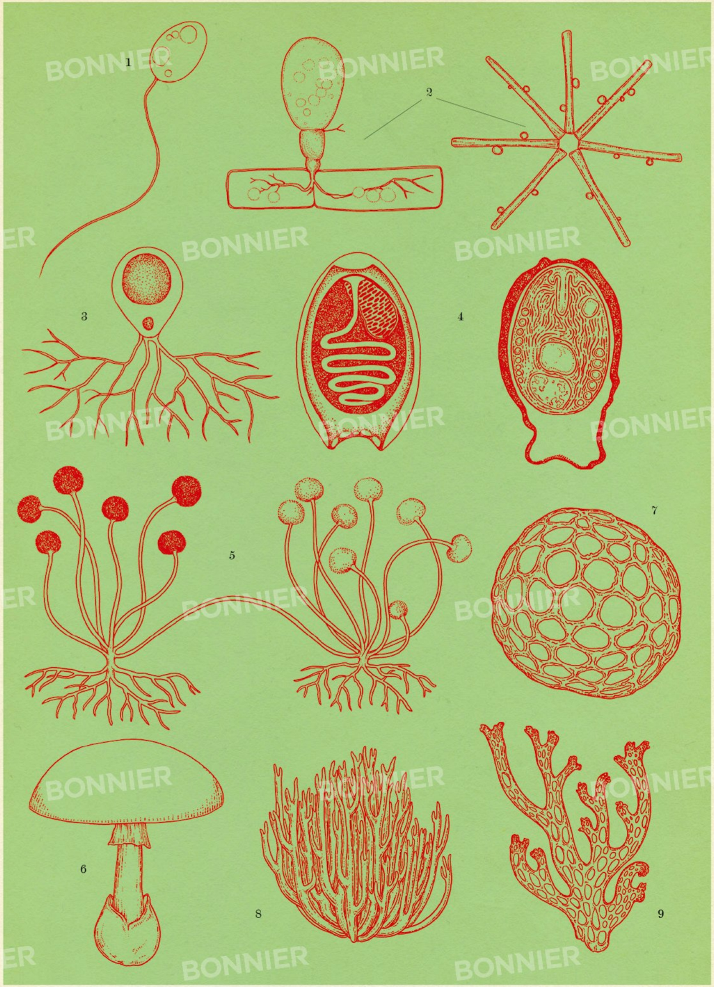
5: Black bread mould
(Mucoromycota)
Rhizopus stolonifer
Mucoromycota have more developed structures than earlier groups, and form networks of filaments, but without the cell-delimiting cross-walls usually found in Ascomycota and Basidiomycota.

6: Caesar's mushroom
(Basidiomycota)
Amanita caesarea
This familiar fungus (also page 54) is found in the phylum Basidiomycota. In basidiomycetes, spores form on microscopic cells known as basidia.

7: Darwin's fungus
(Ascomycota)
Cyttaria darwinii
This belongs to a genus of highly evolved parasitic fungi that only grow on species of southern beech trees. In ascomycete species, spores are formed inside cells known as asci.

8: Upright coral
(Basidiomycota)
Ramaria stricta
This basidiomycete does not look like a typical mushroom. The sporing body has multiple slender and vertical parallel branches covered by spores.

9: ***Cladia aggregata* lichen**
(Ascomycota)
Around 98 per cent of lichens belong to the phylum Ascomycota. *Cladia* presents a unique growth form with numerous perforations along upright extensions of the thallus (the body of the fungus).



Sexual Reproduction

Fungi are very special in terms of reproductive abilities – many of them can reproduce both sexually and asexually. This is rare, and has caused great confusion in the past, as mycologists would often name each reproductive form as distinct species. Even today, scientists may have to use DNA to identify reproductive 'pairs' of the same fungus.

Sexual reproduction in fungi can only be seen with a microscope. When it occurs, two nuclei (the membrane-bound structures that contain the cell's genetic material), each with a single set of chromosomes (thread-like structures in which the DNA is packaged in the nucleus), must fuse together. It is a complex process that involves cell division and the exchange and rearrangement of genes. Living organisms including fungi do this because it ensures genetic diversity, fundamental to evolution and ultimately survival. The fusing nuclei can be from the same individual, or different ones of the same species. Once nuclei are fused, they remain in special cells from which new spore-producing structures arise. The new spores will form new fungal colonies.

In the two largest groups of fungi, Ascomycota and Basidiomycota, the spore producing cells are concealed within structures known as ascomata and basidiomata. In ascomycetes, spores (ascospores) are formed inside sacs called asci, from which they are released in an extraordinary number of ways: the asci may disintegrate to form a spore mass; or forcefully squirt its spores out like a water pistol. By contrast, in basidiomycetes, spores (basidiospores) are produced inside basidia but develop externally on small point-like structures (sterigmata). In mushrooms, basidia form on gills below the caps, and spores are shot bullet-like by an ingeniously moving water droplet – generally just for the tiny distance needed to liberate them from the gills (page 14).

Key to plate

1: Common field mushroom
Agaricus campestris
a) Development of a mushroom, one of many forms that sporing bodies in the phylum Basidiomycota can take. Once the cap opens, the veil breaks and the exposed gills release spores.
b) Portion of an enlarged gill showing basidia and basidiospores on sterigmata.

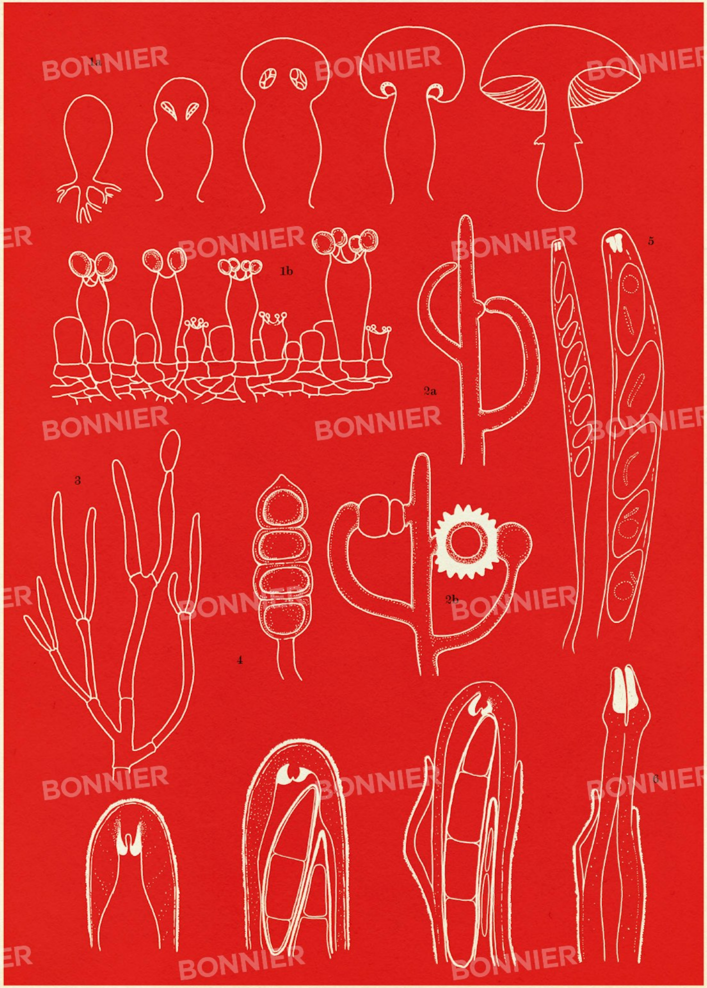
2: *Zygorhynchus* sp.
a) The process of hyphae coming together to form a zygosporangium
b) Zygosporangium and zygospore formed
This fungus has a peculiar reproductive system. Two hyphae come together as sexual partners and are bridged by hyphal tubes which form thick-walled, resistant spores (zygospores) in structures called zygosporangia.

3: Common jellyspot fungus
Dacrymyces stillatus
This typically orange gelatinous fungus stands out for its basidia, which are fork-shaped, branched and produce sausage-shaped spores.

4: Common rust fungus
Phragmidium violaceum
This fungus has a complex life cycle with sexual and asexual stages and different types of spores. The stalked spore (teliospore) includes a row of four cells with two nuclei each. As the teliospore cells germinate, the nuclei fuse and cell division will be followed by the rise of basidia.

5: Candlestick or candle snuff fungus
Xylaria hypoxylon
As in most ascomycetes, the asci of this fungus contain eight spores. Here the spores have a germ slit (a thin area of the cell wall running the length of the spore). There is a huge range of asci types; their structure and method of discharge varies according to their taxonomic group. In *Xylaria* there is an apical structure through which the spores are discharged.

6: Dog lichen
Peltigera canina
This lichen species produces asci with a special form of spore discharge. The ascus wall and its outer layer rupture and the thick apical material of the inner layer expands to form a lip structure (the rostrum). After spore release, the inner layer returns to its place like an accordion.



Asexual Reproduction

Sexual reproduction in fungi can be a complicated and slow process, so many have developed alternative strategies for propagating themselves, establishing new colonies without sex. This is called asexual reproduction. Some fungi produce one or more kinds of asexual reproductive structures as well as sexual ones, while in others no sexual structures are known at all. The advantage of an asexual strategy is that it can produce massive numbers of genetically identical spores, which can rapidly grow on new sites.

Asexual spores are produced by simple cell division and their nuclei have just one set of chromosomes. The most common type of asexual spores are conidia, which form from specialised cells in a mind-blowing number of ways. They can be produced directly from hypha-like structures (conidiophores), from hyphae fused together to form pin-like formations, from mounds in compact groups or even inside a variety of structures (conidiomata) from which they can be discharged through a pore or split. Conidia can form individually, in chains or ball-like clumps and can either be dry or produced in slimy droplets, depending on their method of dispersal (page 14).

There are other asexual ways fungi get around. Yeast cells, which are constantly dividing, can also function as conidia, and separated pieces of hyphae can be carried inadvertently by animals or inside plant tissues. In most cases asexual spores do not travel as far as sexual spores, and only a small proportion end up being widely disseminated by air currents or wind. These are mainly species producing large numbers of small dry spores that often cause allergies.

Key to plate

1: ***Alternaria alternata***
Light brown septate conidia arise forming chains from conidiophores (a hypha that bears conidia). These are produced on mature or dying plant tissue. This is a plant pathogen that causes leaf spot in various plant species and can also cause respiratory infections in humans.

2: ***Coemansia erecta***
Species of *Coemansia* are microscopic saprobes that can be found in dung, soil or other organic materials or from dead animals and insects.
a) Their asexual structures, shown here, present elegant shapes.
b) Here, the spore-bearing structures carry spores lined up, looking like a toothbrush.

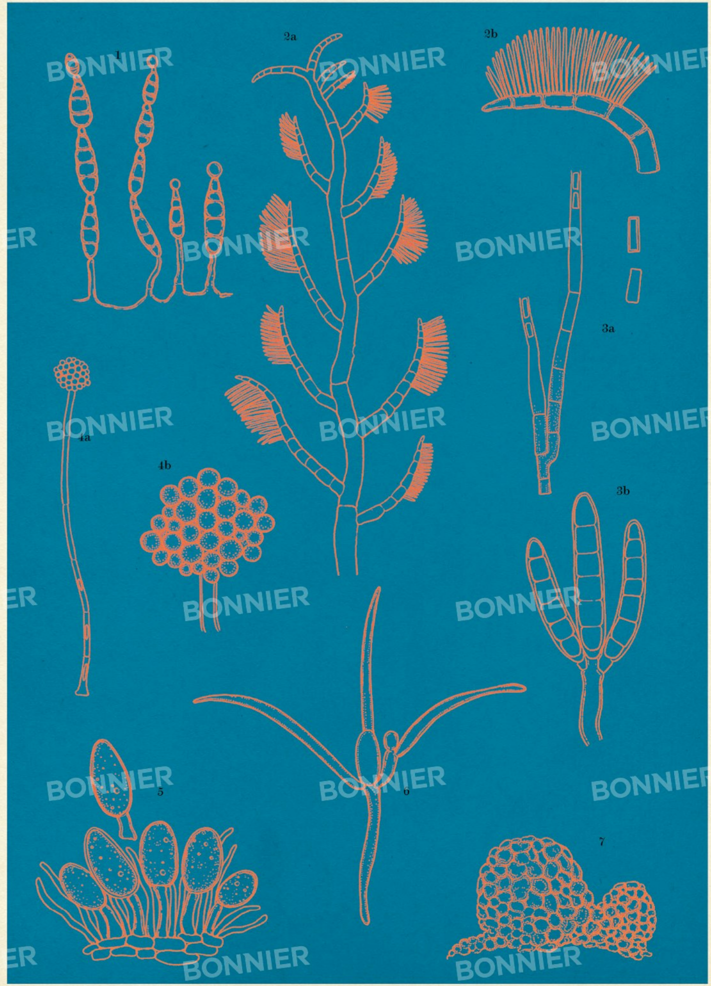
3: ***Thielaviopsis basicola***
This plant pathogen can cause devastating crop diseases, such as black rot or stem-end rot. It can have two types of asexual spores (conidial types):
a) simple tube-shaped conidiophores (translucent) with colourless spores.
b) septate brown spores

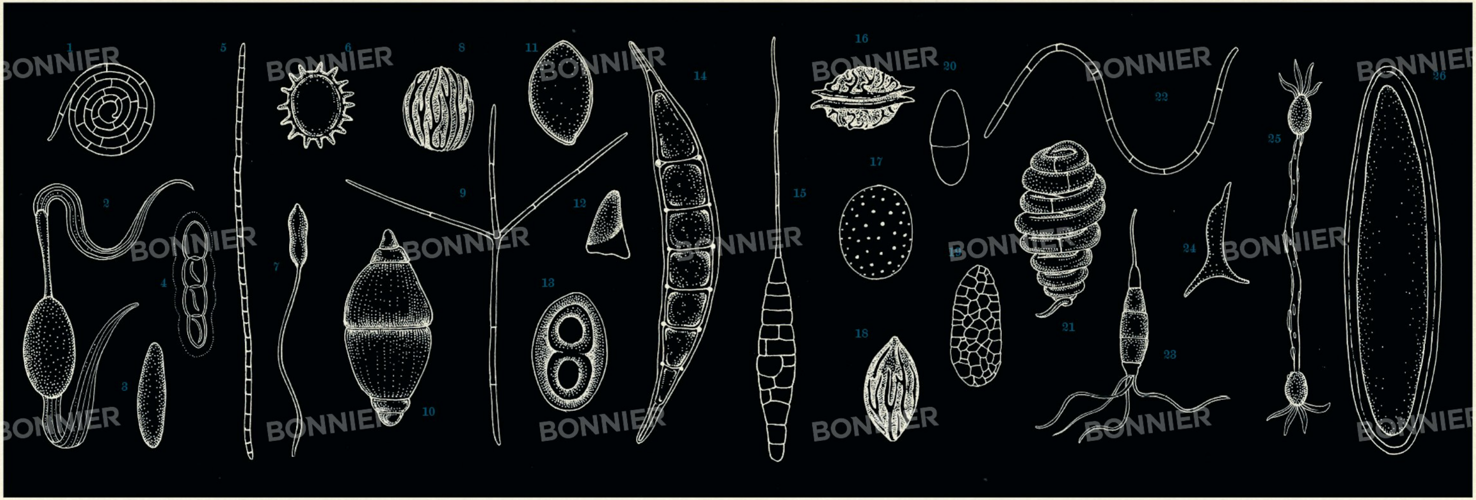
4: ***Periconia byssoides***
This saprobic species can be found on dead plants. It reproduces asexually and is not known to have a sexual stage. In reproduction it forms simple conidiophores that carry many rounded brown, minutely spiny conidia.
a) general view of conidiophore
b) magnified view of conidiophore

5: ***Lasiodiplodia theobromae***
This plant pathogen lives on a wide variety of hosts. It usually causes rotting and dieback in many tropical crops after they have been harvested. Conidia in this species are initially translucent but become darkly coloured.

6: ***Tetracladium sp.***
Tetracladium species are known only from their asexual state, which includes special tetraradiate conidia like the one shown here. *Tetracladium* is aquatic, growing on plant litter in streams.

7: ***Parmelina pastillifera***
Many lichens have the ability to reproduce both sexually and asexually, often simultaneously. The most common lichen structures in asexual reproduction are soralia and isidia, which are able to distribute algal and fungal partners together as single packages. Isidia, seen here, include an outer layer that protects both partners (cortex), whereas soralia do not have a cortex.





Spores

Spores are reproductive cells produced by fungi. The diversity of fungal spores, both sexual and asexual, is truly amazing, from single cells of just a couple of micrometres (a unit of measurement 0.001 millimetres long, shown as µm) to huge ones visible even with the unaided eye. The incredible myriad of shapes found in spores includes minute spheres, enormous ellipsoid structures and delicate threads or coils – some branched, others star-like. Colours vary from transparent to white, pink or various shades of brown to black; sometimes separate cells within a spore have different pigments.

Spore walls can have various layers, and the surfaces can feature all kinds of textures and ornaments, including pores or slits through which they germinate, or scars produced when they are formed. Some have outer coatings, including jelly-like sheaths or appendages ranging from almost invisible whip-like threads to complex gelatinous heads and tails. Beneath the outer layers, many have internal walls making several compartments, which can germinate independently.

The form of the spores, and whether they are dry or slimy, depends on their method of dispersal. Some stick together to form massive projectiles, which when ejected, can travel half a metre or more, while others split into part-spores to increase the number of dispersal units (propagules) and establish new colonies. There is a misunderstanding that fungal spores are easily distributed in the air. In reality most do not travel far at all on their own as they are formed too close to the ground to get high. Some are specially adapted to dispersal by insects, birds or mammals. Truffles, for example, produce their spores in sporing bodies below ground that release a special aroma to attract mammals, which will help dispersal. Some elaborate spores with long arms are adapted to disperse in water.

Key to plate

1: ***Helicomyces scandens*** (20µm)
2: ***Podospora fimiseda*** (360µm)
3: ***Xerocomus badius*** (12µm)
4: ***Sporormiella leporina*** (35µm)
5: ***Schizoxylon ligustri*** (125µm)
6: ***Russula viridofusca*** (12µm)
7: ***Harknessia spermatoidea*** (120µm)
8: ***Ustilago koenigiae*** (12µm)
9: ***Tetrachaetum elegans*** (250µm)
10: ***Caryospora callicarpa*** (75µm)
11: ***Lophotrichus ampullus*** (10µm)
12: ***Triangularia bambusae*** (25µm)
13: ***Rinodina confragosula*** (28µm)
14: ***Corollospora lacera*** (65µm)
15: ***Alternaria sesami*** (400µm)
16: ***Penicillium baarnense*** (6µm)
17: ***Gelasinospora micropertusa*** (40µm)
18: ***Neurospora lineolata*** (20µm)
19: ***Calenia monospora*** (65µm)
20: ***Neonectria ditissima*** (12µm)
21: ***Helicoon ellipticum*** (40µm)
22: ***Anguillospora longissima*** (240µm)
23: ***Pestalotiopsis guepinii*** (45µm)
24: ***Cornutispora lichenicola*** (15µm)
25: ***Zygopleurage zygospora*** (285µm)
26: ***Pertusaria pertusa*** (220µm)

Note: measurements shown are length or longest axis

Growth

All filamentous fungi are made from narrow, cylindrical tubes called hyphae. These are usually less than ten micrometres wide and have tough walls containing chitin (page 8). Hyphae are filled with liquid kept under high pressure by taking in water through their walls. Most are divided by cross-walls so that they look like the cells of animals and plants, but their internal structures (organelles) can move freely through compartments as the cell contents flow stream-like. They grow from their tips, which contain specific organelles to generate new wall tissue. Masses of branching hyphae together form what is known as a mycelium.

Hyphae can act like hydraulic rams, puncturing the surfaces of leaves, forcing themselves through soils, wood and even penetrating rock surfaces – aided by the release of enzymes or organic acids from their tips that break down material as they grow. Their branching patterns vary according to the availability of food, becoming dense in a radial manner when they find nutrients. Sometimes they twist themselves into whitish rope-like cords or even dark brown boot-lace-like strands (rhizomorphs).

Not all fungi form hyphae all of the time, or in some cases at all. Yeasts are single-celled and divide repeatedly by 'budding', forming mounded, circular superficial colonies. Some can also produce hyphae when invading tissues, while filamentous fungi can have yeast-like stages in their life cycles. Chytrids living in moist or aquatic environments are almost invariably single-celled and never form colonies.

Growth rates vary enormously. Humidity and temperature are the key – species have optimal conditions to match their ecology. Pin moulds such as *Mucor* species can cover a slice of damp bread in a few days, while a lichen fungus on a rock may only increase a few millimetres a year. Human pathogens will grow best at body temperature, while fungi of hot deserts favour mid-40s Celsius.

Growth rates are of practical importance too. They can help date how long an object (even a corpse) has been in a place, or in the case of lichens, when a roof was built, or a glacial moraine was deposited – a technique known as lichenometry by glaciologists.

Key to plate

1: Blue mould rot fungus on apple
Penicillium expansum
When growing on a nutrient-rich surface like an apple, the hyphae of this fungi branch repeatedly in a radial manner, forming circular patches. In some fungi, if there is a shortage of nutrients, the hyphae will spread out and forage for something to digest, and when they find it will concentrate around it.

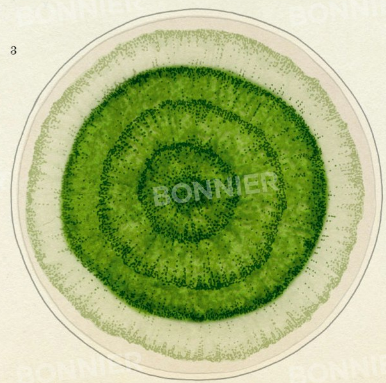
2: Toxic black mould
Stachybotrys chartarum
Seen growing on cellulosic material
Characterised by conidia that can be seen under a lens, this species occurs in warm, damp conditions and can be found in homes and buildings. It is one of a complex of species that has been linked to health issues in humans and animals.

3: ***Trichoderma viride***
Seen on a culture plate displaying typical radial growth
Some fast-growing species of this genus can be cultivated to combat the spread of fungal pathogens in various plants including cotton, tobacco and sugar cane.

1

2

3



Ecosystem: Mountains

From peak to base, and across snow-covered landscapes, bare stone and luscious forests, mountains provide a diverse range of environments in which many different fungi occur; some of them cannot be found anywhere else in the world. The fungi that live here need to adapt to the severe conditions that become harsher with increasing elevation. Above the treeline, the alpine zone is characterised by short, open vegetation (mostly grasses and small woody plants), low temperatures and high exposure to sun and wind. Here, the ground is covered by snow most of the year. At lower elevations, conditions are less harsh, and trees can grow in deeper and richer soils. The environmental characteristics in each zone shape the communities of fungi and plants that exist there.

At high altitudes, ectomycorrhizal fungi (pages 38–39) are essential for the survival of small alpine woody plants like species of dwarf willows (*Salix*) or mountain avens (*Dryas octopetala*), as well as herbaceous plants like the alpine bistort (*Bistorta vivipara*) and false sedge (*Kobresia*). Fungi here can only fruit during the short period of time after the snow melts and do so much earlier than at lower elevations where the fruiting period is usually longer. The most abundant ectomycorrhizal fungi in alpine habitats above the treeline, include webcaps (*Cortinarius*), fibrecaps (*Inocybe*), poisonpies (*Hebeloma*), deceivers (*Laccaria*), pinkgills (*Entoloma*), milkcaps (*Lactarius*) and brittlegills (*Russula*), which all form gilled mushrooms. Less familiar and detectable, but equally abundant, are crust-like fungi including *Tomentella* and some *Sebacina* species, found under rocks, on soil or decaying wood. Above the treeline lichens can dominate, growing on exposed rock surfaces.

Below the treeline and in the litter layer in the forest (made up of mainly dead plant material on the surface of the soil), other mycorrhizal fungi, such as boletes like *Suillus* and *Leccinum* can be seen, alongside decomposers such as jelly fungi (*Calocera*, staghorns). The stinking parachute (*Gymopus perforans*), a tiny marasmioid fungus, can also be found in forests.

Key to plate

1: Alpine webcap
Cortinarius alpinus
Seen here forming a symbiotic relationship with the roots of the dwarf willow *Salix herbacea*, the small fruiting bodies of the alpine webcap are taller than their plant host.

2: Alpine brittlegill
Russula nana
This beautiful small mushroom forms a symbiotic relationship with the roots of the alpine bistort, *Bistorta vivipara*, but it can live in symbiosis with other Arctic or alpine plant species.

3: Favre's fibrecap
Inocybe favrei
This mushroom forms a symbiotic relationship with the roots of mountain avens (*Dryas octopetala*), seen here. It is named after the pioneering Swiss geologist Jules Favre.

4: Gassy webcap
Cortinarius traganus
The violet fruiting body of this fungus is well known for its strong, unpleasant scent. It forms symbiotic relationships with roots of pine and birch trees.

5: Yellow stagshorn
Calocera viscosa
This fiery bright fungus grows in dead wood. The name '*calocera*' means 'beautiful and waxy', while '*viscosa*' means sticky. This is fitting, as it can be used as a chewing gum.

6: Stinking parachute
Gymnopus perforans
These miniature fungi form sporing bodies around fallen conifer needles. Despite their small size, they smell strongly of rotten cabbage.

7: Weeping bolete
Suillus granulatus
With a greasy cap and dots on the stipe (stem), this mushroom forms a symbiotic relationship with the roots of pine trees. When young, it releases milky droplets that give it its name.

8: Orange birch bolete
Leccinum versipelle
This large bolete forms a symbiotic relationship only with birch trees.

Gallery 2

Fungal Diversity

Cup Fungi

Cup-shaped sporing bodies, often known as 'apothecia,' are produced by a wide range of groups within the fungal kingdom, mostly belonging to the ascomycetes. Despite their relatively simple structure, they have an enormous variety of forms, many of which are eye-catching and beautiful. Some are extremely tiny (less than a millimetre in diameter) and can only be seen clearly with a hand lens or microscope, while others can reach 10 centimetres or more. They are often brightly coloured, and some have short or long stalks, while others have eyelash-like hairs. Many lichens (page 40) also produce tiny cups to spread their spores.

Most cup fungi are spore shooters. The inside of the cup is lined with spore-bearing tissue and when the cup is mature and the weather conditions are just right, spores are shot out at high speed in a synchronised 'puff'. In some of the larger cup fungi this can be triggered by blowing on them, resulting in the release of a smoky cloud of spores.

Because the sporing bodies of most cup fungi are fleshy and soft, they are prone to drying out. These species prefer damp habitats and are intolerant of dry conditions, although there are exceptions. This diverse group is found in a wide range of habitats from beaches to scorched earth, from animal dung to dead plant matter, and even appears on carpets and the walls of houses. Most live and feed on dead plant material or soil, and in turn become food for other organisms such as insects. Some even form mutually beneficial relationships with tree roots, or with plants such as mosses (mycorrhiza). One group has evolved to catch very tiny eel-worms (nematodes) with sticky knobs or lassos.

Key to plate

1: Spring orange peel fungus
Caloscypha fulgens
This golden-coloured species is named for its appearance, which resembles discarded fruit peel.

2: ***Plectania chilensis***
This fungus occurs on wood in the Southern Hemisphere.

3: Scarlet elf cap
Sarcoscypha austriaca
The name of this vibrant species means 'from Austria', where it is commonly found, although it also occurs in other parts of Europe and North America. It thrives on decaying organic matter, and in damp conditions amongst mosses and leaf litter.

4: ***Cookeina speciosa***
This beautiful, pinkish red fungus forms sporing bodies which look like velvety goblets. It is found in the forests of the neotropics growing on rotting wood on the forest floor. (also page 58)

5: Eyelash fungus
Scutellinia scutellata
The bright discs have black eyelash-like hairs along the margin that fold inwards over much of the disc when conditions are dry. It is often found on damp, rotten timber on woodland floors. Several similar species differ in the details of their spores.

6: Orange peel fungus
Aleuria aurantia
This fungus begins as a cup shape, but twists and contorts itself to resemble an orange peel, often splitting in the process.

7: Hare's ear
Otidea onotica
Found in many parts of Europe and North America, this golden-coloured fungus commonly lines the pathways of well-trodden routes through temperate woodland.

8: Black earth tongue
Trichoglossum hirsutum
Velvety in texture and with spear-headed sporing bodies, this darkly-coloured fungus occurs in acidic soils.

9: Green elf cup
Chlorociboria aeruginosa
This species produces a vivid blue-green pigment which can be used to stain wood. Historically, this was used in decorative woodwork, known as 'Tunbridge ware'.

Mushrooms and Toadstools

When people think about fungi, they usually envisage mushrooms or toadstools. These are the fleshy sporing bodies often seen growing in soil or on wood. Mushrooms and toadstools come in all colours of the rainbow and in many different sizes; from a tiny purple *Cortinarius bibulus* with a cap diameter of about 5 millimetres, to *Termitomyces titanicus* which is 200 times larger and has a cap diameter up to 1 metre.

'Mushroom' and 'toadstool' are not scientific terms, but are used to describe sporing bodies with a similar appearance. These belong to many orders of fungi. The sporing bodies we call mushrooms are fleshy and have a cap, gills and a stipe (stem). Sometimes the word 'mushroom' is only used for edible fungi, though it can apply to toadstools as well. The word 'toadstool' is usually applied to fungi that are inedible or poisonous. The best known is the striking red and white fly agaric (*Amanita muscaria*). The name toadstool originates from the medieval idea that toads, considered carriers of poison, liked to sit on these sporing bodies.

An interesting phenomenon which occurs only in mushrooms is fairy rings. These appear when mushrooms or toadstools grow in an arc or ring. They can be found in woodlands and grasslands and are produced by over fifty different species including the edible fairy ring fungus (*Marasmius oreades*). The centre of the ring is where the fungus has started its growth. The ring of mushrooms is produced behind the edge of the growing structure of the fungus (mycelium).

One of the most colourful mushroom groups is the waxcaps (*Hygrocybe* spp.). The sporing bodies of waxcaps come in wonderful shades of red, orange and yellow, while some species are also green or pinkish purple. Some of them are only found on nutrient-poor grasslands, habitats that are declining. In the United Kingdom, the growth of waxcaps on grassland is used as a measure of whether the site should be legally protected.

Key to plate

1: Shaggy ink cap
Coprinus comatus
This species is often found on lawns. It grows in groups and has a beautiful white, scaly cap and gills which secrete a black 'ink' when maturing. This fungus can kill and digest nematodes (roundworms) for extra nutrition.

2: Fly agaric
Amanita muscaria
This widespread species has been used to catch flies and also in religious rituals by shamans because of its hallucinogenic properties.

3: Shaggy scalycap
Pholiota squarrosa
A common parasitic fungus, this can be found growing in clusters at the base of stumps and trees. It is covered in scales, which makes it easy to recognise.

4: Violet webcap
Cortinarius violaceus
The easiest *Cortinarius* species to recognise, this beautiful, big, violet mushroom occurs in Europe and North America.

5: Blue roundhead
Stropharia caerulea
Because of its blue colouring, this species is easy to spot. It is a saprophyte, meaning it doesn't need a host tree and instead gains nutrition from decaying organic matter.

6: Waxcaps
Hygrocybe spp.
a, b, c, d) As shown here, waxcaps are bright spots of colour, often seen on long-established grasslands and lawns. Some grassland waxcaps are especially rare.

Bracket Fungi

While most mushrooms produce their spores inside gills, bracket fungi (or polypores) form sporing bodies with pores or tubes on their underside. In most cases, they are as hard as the wood of the trees they grow on. They make shelf- or bracket-shaped, or – more rarely – circular bodies that are often called 'conks'. Like most mushrooms they belong to the Basidiomycota (page 5) and it seems that they have appeared independently multiple times in the evolution of the fungal kingdom.

Bracket fungi are wood decayers, growing mainly on tree trunks and branches, but a few exceptions can form mycorrhizas (pages 36–39) with trees. They are the only organisms able to break down the tough compounds that make up lignin found in wood and so without bracket fungi (and their relatives, corticioid fungi – 'crust fungi' living mostly on the undersides of dead tree trunks or branches) forests would be covered in wood and leaf litter! That is why they are vital for nutrient cycling and carbon dioxide release in forest ecosystems. On the other hand, some of them are severe pathogens of trees, and are major causes of damage to timber.

But bracket fungi are not only important for ecosystems, they have been used by humans since ancient times. The tinder fungus (*Fomes fomentarius*), a common and widely distributed species, is easy to find and recognise and it has been used to make clothing such as caps. It is best known, however, for its application as tinder. The species was found with Ötzi the Iceman, a mummified prehistoric person found in Europe's Ötztal Alps. It is thought that he may have been carrying it to make fire.

Another bracket fungus used by humans is chaga (*Inonotus obliquus*). It is believed to suppress cancer progression and enhance our immune system. This species looks like burnt coal and can be found growing on the trunks of mature birch trees.

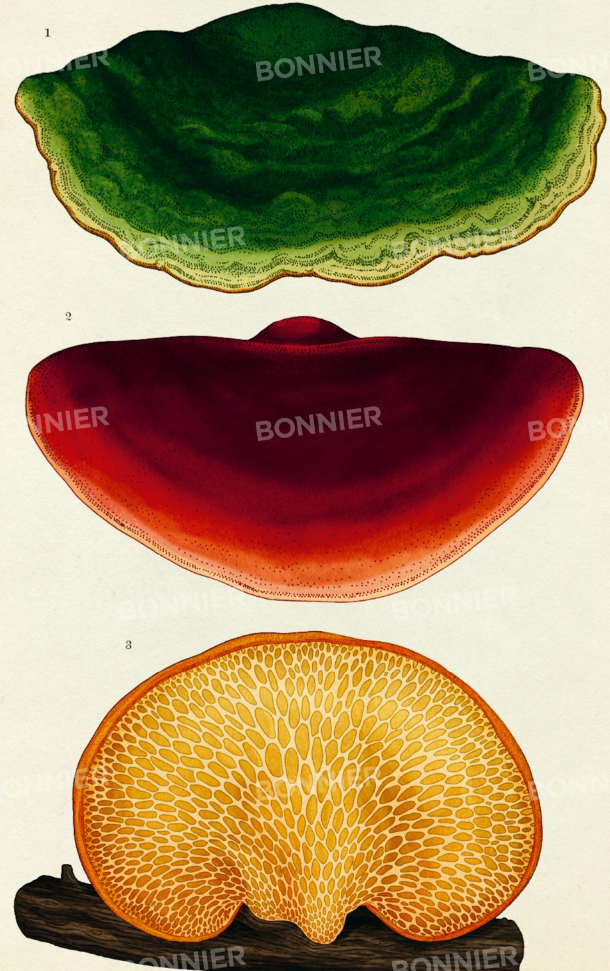
Some bracket fungi can be used to indicate that a forest is ancient. These species are very sensitive to the impact of human activities; once they have disappeared, they may never return and some may become extinct.

Key to plate

1: Giant elm bracket
Rigidoporus ulmarius
This fungal pathogen grows mostly on broad-leaved trees such as elm. The brackets are usually whitish to cream, but they often become green due to the growth of green algae. For many years a bracket of *Rigidoporus ulmarius* in Kew Gardens was the largest known fungus ever discovered, with a circumference of about 5 metres. Bracket fungi generally grow concentrically and they often show bands of growth.

2: Beefsteak fungus
Fistulina hepatica
As its common name indicates, this species has the appearance of raw meat. It was actually used as a meat substitute in the past and its consistency is fleshy and bleeds a red juice when cut. Red on the top, the underside is a white mass of tiny tubes (a reduction of the typical gills). Its Latin name *hepatica* means 'liver-like'.

3: Oak polypore
Buglossoporus quercinus
Underside of bracket
This rare polypore is found on ancient oaks in old growth woodlands and pastures where exposed heartwood is present. Given their slow growth, narrow range of environmental conditions and that their habitat is in decline, this species is under threat and has the highest level of legal protection in the United Kingdom. It has recently been added to the IUCN Red List of Threatened Species.



Gasteromycetes

Gasteromycetes are fungi that share similar reproductive strategies, even though they are not closely related. Often, though not always, they are saprophytic, meaning they derive their food by breaking down organic material in the soil. In doing so they play an important role in the ecosystem because they recycle nutrients.

Unlike other mushroom-forming fungi, gasteromycetes do not have the ability to forcibly disperse their spores from gills or pores. They produce spores on the inside of their sporing bodies and have developed different strategies to disperse them. This, in turn, has led to the evolution of unusual and strikingly beautiful mushroom forms.

The simplest kinds of spore dispersal take place in puffballs. These fungi have round sporing bodies ranging in size from just a few millimetres wide to something bigger than a watermelon. In some, the spore-rich mass on their inside needs physical contact to be ejected. This can be anything from falling raindrops to more vigorous actions such as being knocked by an animal walking past. Some puffballs have small holes out of which spore masses can be puffed out, others simply split open. Earthstars have evolved a similar appearance to puffballs, with a small pore at the top, out of which spores are released when touched.

Bird's nest fungi make use of raindrops to disperse their spores. Their sporing bodies are shaped like specialised 'splash cups', and the spores held in sacs at the base look like eggs. Raindrops hitting the inside of the cup force the spore sacs to be ejected. In some cases, the sacs are eaten by animals and so are further dispersed – and fertilised – in their dung.

Complex and unusual spore-forming bodies are found in the stinkhorn fungi. This weird and wonderful family all produce a brownish, spore-rich liquid called gleba over their surfaces. Gleba is foul-smelling – like rotting meat and faeces – and attracts insects who like these food sources. The insects disperse the spores when they fly away with gleba stuck to them.

Key to plate

1: Common puffball
Lycoperdon perlatum
The cream outer flesh of this fungus is covered with tiny bumps and spikes, and becomes brown when mature. At this stage, a small pore opens at the apex, which the spores burst from.

2: Sculpted puffball
Calvatia sculpta
This unusual-looking puffball has pyramid-shaped growths on its outer surface, through which spores are released.

3: Bird's nest fungus
Cyathus striatus
This widespread fungus can often be found growing on mulch and compost in gardens and holds the spores in pellet-like sacs (peridioles).

4: Stinkhorn fungus
Colus hirudinosus
The cage-like structure of this fungus intensifies from a light orange at the base to a dark red at the tip and emerges from a gelatinous white 'egg'. Despite its beauty, it has an odour similar to faeces. It is edible.

5: Earthstar fungus
Geastrum quadrifidum
Starting out as small, grey-brown balls, the outer layer of this fungus splits into a star-shaped base, which exposes the central spore case and thrusts it upward, where it can more easily disperse the spores.

6: Rounded earthstar
Geastrum saccatum
The immature egg-shaped sporing body of this species eventually splits, with the outer layer curving to the base to reveal a spore case at the centre. It is found throughout the world.

7: Veiled lady
Phallus indusiatus
Another member of the stinkhorn family, the delicate veil around the sporing body doesn't disguise the fact this fungus smells truly foul.

8: Common earthball
Scleroderma citrinum
a) Unlike most other gasteromycetes, this fungus is mycorrhizal, forming symbiotic relationships with some tree species and woody shrubs.
b) When opened, it reveals a dark, purple-black gleba (interior), and is toxic if eaten. (also page 32)

Foliicolous Fungi

In tropical forests, many leaves look like they have beautiful mosaics on their surfaces. These are mostly fungi. In these habitats, trees are evergreen and individual leaves can be very large and live for many years. A wide variety of fungi have evolved to use them as places to live but, unlike plant pathogenic fungi, without invading and killing them.

These benign fungi are known as 'foliicolous'. They do not penetrate the living cells of the leaves, though they can have special bodies to attach them to the surface or, in some cases, grow between the plant cuticle (protective film covering the epidermis) and the living parts of epidermis cells. They gain nutrients from the water dripping from the forest canopy, not from the leaves they grow on. A number are lichen-forming and capture leaf-dwelling green algae to secure a supply of sugars. As non-lichen fungi do not need light to photosynthesise, some groups only grow on the underside of leaves.

Many foliicolous fungi form rosettes, made up of shield-like, radiating hyphae covering their spore-producing structures. These superficial hyphae are often dark brown to black (melanised) to help resistance to desiccation in times of drought. These are often visible as delicate networks criss-crossing the leaf surfaces when viewed with a lens.

There are concerns that excessive growths of these organisms can adversely affect tree health, for example in oil palm and tea plantations, but some studies in Australia suggest that colonised leaves compensate by producing more chlorophyll in their uncolonised parts. Foliicolous fungi are also an important habitat for other fungi (fungicolous fungi) that only live on particular foliicolous species, growing on superficial hyphae where they also seem to be benign. While mainly a feature of the humid tropics, there are a few foliicolous species able to grow on evergreen leaves, including box, holly, juniper and laurel in temperate regions.

Key to plate

1: ***Meliola urariae***
Typical branching of a superficial hypha and specialised hyphal branches composed of one-lobed cells, which attach the fungus to the leaf and help absorb food (hyphopodia). Species in the family Meliolaceae mostly live biotrophically (establishing symbiosis) on leaves and stems of particular plants.

2: Leaf
Seen with a mixture of fungal colonies on its surface, including some lichens.

3: ***Strigula orbicularis***
a) Sporing bodies and thallus
b) Section of a sporing body with plant cuticle layer on top and epidermal cells in a layer below

4: ***Tricharia urceolata***
This lichen is strictly tropical and abundant in South America. Species of *Tricharia* produce hair-like structures named 'hyphophores', which are highly specialised conidia-producing structures.

5: ***Parenglerula macowanianus***
a) Example of mycelium growth on a leaf with hyphopodia and dark rounded sporing bodies (ascomata)
b) Section of a sporing body growing on leaf surface showing several asci, one of them full of spores

6: Shield fungus
Lichenopeltella palustris
This specialised flattened sporing body, known as a 'partial thyriothecium', has a wall of quadrangular cells arranged in radiating rows that grow on the leaf, and a 'central ostiole' (rounded aperture) crowned by a series of black hair-like structures (setae) through which spores are released.

7: ***Peltistroma juruanum***
Colonies of the fungus are here seen growing on a section of a leaf.

Ecosystem: Temperate Forests

With fertile soils, plenty of rain and seasonal weather, temperate forests make ideal homes for fungi. Oak and beech are common deciduous trees in these forests and harbour more fungi than other native trees in Europe. Here, fungi play an important role by decaying organic matter (saprotrophs), enhancing tree growth by forming symbiotic relationships with their roots (ectomycorrhizal fungi, pages 36–39) or associating with algae and cyanobacteria to form lichens.

Some saprotrophs are root-inhabitants of these trees, such as the zoned rosette (*Podoscypha multizonata*) that forms coral-like concentric fans, and the gilled mushroom spindle toughshank (*Gymnopus fusipes*). Others can be found on trunk heartwood (the dense, inner core of the trunk), on lower branches of living trees and on fallen wood. Examples of these include chicken of the woods (*Laetiporus sulphureus*), a bracket fungus which causes brown rot and occurs on trunks, and beefsteak fungus (*Fistulina hepatica*) with liver-like red brackets. *Mycena inclinata* is another saprotroph usually found on fallen branches and recognised by its distinctive oily and soapy smell.

In temperate ecosystems, fungi can also signal environmental conditions. The oak milkcap (*Lactarius quietus*) is an indicator of high nitrogen pollution and soil acidification – two of the main threats to temperate forests in Europe – while the lichen tree lungwort (*Lobaria pulmonaria*) thrives in ancient woodlands with low pollution levels, making it a good indicator of clean habitats.

Key to plate

1: Oakmoss lichen
Evernia prunastri
Found growing on the trunk and twigs of trees and shrubs, this decoratively branched lichen resembles deer antlers.

2: Chicken of the woods
Laetiporus sulphureus
So-called because its texture and consistency are similar to cooked chicken.

3: Beefsteak fungus
Fistulina hepatica
(also page 26)

4: Zoned rosette
Podoscypha multizonata
This striking, rare fungus grows on soil around oak trees.

5: Spindle toughshank
Gymnopus fusipes
This common species is usually found in clumps where the tree trunk meets the soil and causes root rot in oaks.
It grows amongst roots from dormant, hardened structures called sclerotia.

6: Oak milkcap
Lactarius quietus
In ectomycorrhizal symbiosis with the roots of oak trees, the oak milkcap has gills that when cut or torn release a milky latex.

7: Clustered bonnet
Mycena inclinata
This mushroom is a saprotroph often found on fallen branches.

8: Yellowfoot or trumpet chanterelle
Craterellus tubaeformis
Appearing in large groups, these edible chanterelles form ectomycorrhizas with the roots of oaks. This makes it very difficult to grow them commercially.

9: Coral fungi
Ramaria sp.
This fungus occurs abundantly in temperate forests, forming coral-like sporing bodies on soil.

10: Beech or slimy milkcap
Lactarius blennius
This fungus lives in association with the roots of beech trees and is native to Europe. 'Blennius' means 'slimy', and describes the cap's surface.

11: Common earthball
Scleroderma citrinum
This ectomycorrhizal fungus forms relationships with oak and beech roots in acidic soils. The inner part of the body (gleba) contains dark spores (also page 28).

12: Matt bolete
Xerocomellus pruinatus
This bolete is native to Europe, and lives in association with the roots of beech and oak trees. It produces mushrooms that, under the cap, have yellow tubes that end in pores instead of gills, which harbour the spores.

13: Tree lungwort
Lobaria pulmonaria
This lung-shaped lichen is formed by association with three different organisms – a fungus, an alga and a cyanobacterium.

FUNGARIUM

Gallery 3

Fungal Interactions

Mycorrhizas
Mycorrhizal Networks
Lichens
Entomogenous Fungi
Ants and Termites

Mycorrhizas

Hidden to our eyes most of the time and living in the soil under our feet, there are fungi that form associations with plant roots, forming mycorrhizas. These are ancient, symbiotic (mutually beneficial) relationships between certain fungi and most plants on Earth and they evolved millions of years ago to help the first plants establish on the land and successfully grow in nutrient-poor environments. Even now, 90 per cent of the plants on Earth still cannot live without these fungi in their roots!

Mycorrhizal fungi colonise the roots of plants. They provide the plants with water and nutrients from the soil that the plants cannot obtain themselves. In return, the fungi obtain plant carbohydrates which they need to grow. Different fungi associate with different plants forming four main types of mycorrhizas: arbuscular mycorrhizas; ectomycorrhizas; ericoid mycorrhizas; and orchid mycorrhizas.

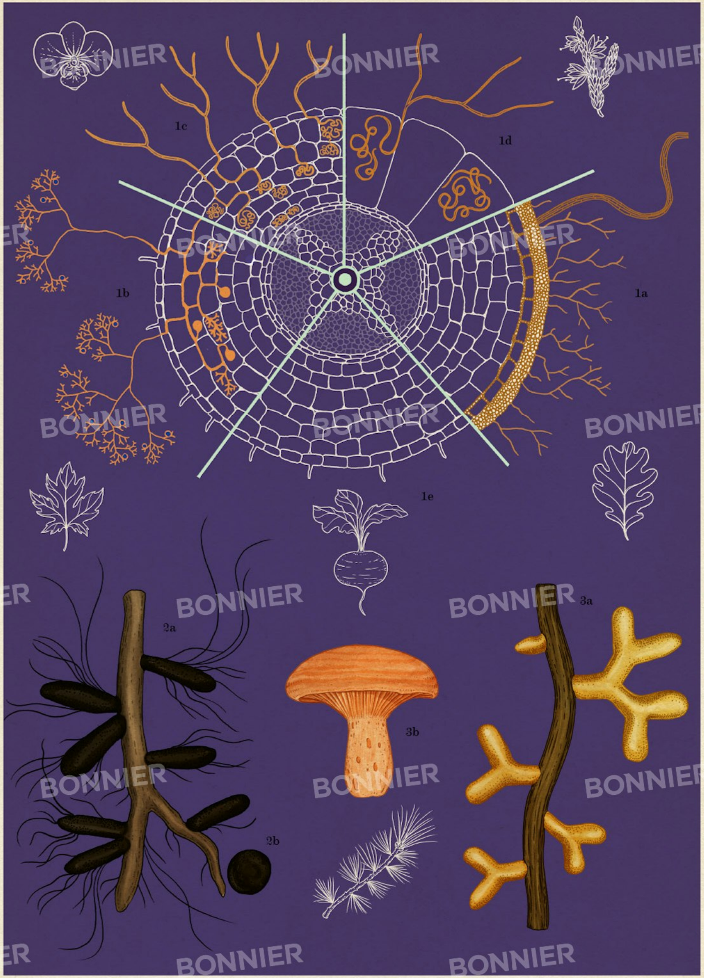
Around 80 per cent of all plants (including fruit trees, most grasses and food crops) form arbuscular mycorrhizas, which specialise in absorbing phosphorus from soil. This nutrient is limited in the soils where these plants grow. Only around 2 per cent of plants form associations with ectomycorrhizal fungi, including many edible ones like chanterelles, truffles and porcini. These fungi specialise in the uptake of nitrogen and associate with woody plants including oaks, pines, beech and gum trees. Ericoid mycorrhizal fungi colonise the roots of plants of the Ericaceae family (including heathers, blueberries and rhododendrons) and some liverworts, unlocking nutrients for their host plants. Orchids are also dependent on mycorrhizal fungi and cannot germinate without them. They also need these fungi in their first stages of development.

Key to plate

1: Cross section of a root showing the four main types of mycorrhizas
a) Ectomycorrhizas
The fungal filaments surround the feeder roots forming a sheath of fungal tissue (mantle) and extending into the soil. They also grow between the roots' cells forming the 'Hartig net', where the nutrient exchange between fungus and plant takes place.
b) Arbuscular mycorrhizas
The fungal filaments form structures (arbuscules) and/or vesicles (sacs for storage) inside the plant root cells.
c) Orchid mycorrhizas
The fungal filaments penetrate the root cell walls and form coils called pelotons that can be reabsorbed by the plant. The seeds of orchids do not have nutrients, so orchids rely in these fungi to germinate.
d) Ericoid mycorrhizas
The fungal filaments penetrate the root cell walls forming coils. This mycorrhizal type is abundant in heathlands, tundra and boreal ecosystems where the fungi help the plants to compete for nutrients in very poor soils.
e) Non-mycorrhizal
Root with no fungal tissue present

2: ***Cenococcum geophilum***
a) This ascomycete has one name, but actually comprises a complex of species that colonise the roots of over 200 different plant hosts forming ectomycorrhizas. These are easily spotted because of their black colour and thick fungal filaments.
b) Despite being abundant in the roots, they do not form sporing bodies, but they can remain in soil for hundreds of years in the form of dormant structures called sclerotia, as seen here.

3. Saffron milkcap
Lactarius deliciosus
a) This is how this fungus looks in the roots of pine, forming ectomycorrhizas. Its ectomycorrhizas are characterised by their smooth and bright orange surfaces (mantles) and the dichotomous branching pattern of the pine.
b) The orange mushroom is the edible sporing body, and is only seen in autumn. Its gills release orange latex when torn or cut.



Mycorrhizal Networks

Mycorrhizal fungi are connected to the roots of their host plants forming mycorrhizas. These extend into the soil through their fungal filaments. One fungus can be attached to the roots of many plants (of the same or different species) and one plant can be attached to many different fungi. A tree can harbour dozens of fungi in its roots. In this way, plants can be connected to each other below ground through their roots by these fungi, forming the 'wood wide web'.

The interconnected filaments that the fungi form can be as vast and complex as forests. Sometimes we see evidence of them above ground in the form of mushrooms or crusts, and below ground in the form of truffles. These are just the tip of the iceberg; the sporing bodies of the huge below-ground functional part of these fungi. These form extraordinarily complex communication systems known as mycorrhizal networks. In fact, a gram of soil can contain hundreds and hundreds of these fungal filaments.

Each fine root of an oak tree, as in many other trees in temperate and boreal ecosystems, is fully sheathed by a fungus which forms an ectomycorrhiza (page 36) structure formed by fungus and root). These allow the mycorrhizal network to take shape. From the ectomycorrhizas, fungal filaments extend deep into the soil, gathering nutrients and water. These are transferred to trees in exchange for plant carbohydrates that the fungi use for their own growth and to form sporing bodies.

Mycorrhizal networks are not just created by ectomycorrhizal fungi and amongst trees. For example, arbuscular mycorrhizal fungi form networks in grasslands, where there are no trees. Mycorrhizal networks are useful to plants because the fungal filaments increase the surface of absorption and can access nutrients and water that plant roots and root hairs cannot reach. They also help the soil particles to stick together, which enhances soil stability, prevents erosion and, by transferring water and nutrients, can support the growth of seedlings under the shade of mature trees.

Key to plate

1: Mature English oak and young seedlings
Quercus robur
Oak trees and seedlings are connected below ground through mycorrhizal networks.

2: Sporing bodies
The mushrooms and truffles of ectomycorrhizal fungi are attached to the roots of the tree and seedlings through the ectomycorrhizas.

3: Ectomycorrhizas and fungal filaments
From the ectomycorrhizas, the fungal filaments extend into the soil gathering nutrients and water that they exchange with the host for sugars, but they also connect trees below ground by forming new ectomycorrhizas in other roots. This system, formed by fungal filaments, is called a mycorrhizal network.

Lichens

Lichens are the result of highly successful mutualistic relationships between fungi (mycobionts) and at least one other photosynthesising organism (photobiont), which can be either an alga, a cyanobacterium or both. The fungus benefits from the sugars produced by the photobiont, and the photobiont benefits from a place to live, physical protection and better access to mineral nutrients. In fact, lichens are so well integrated that they were historically studied as one single species. Today, we know that nearly one fifth of all known fungal species form lichens. More than 98 per cent belong to the largest fungal phylum, Ascomycota, with a few species classified within Basidiomycota (page 5).

Lichens come in a huge array of shapes and colours. They can be crusty, leafy or shrub- or hair-like, and grow on almost any surface they can find: rocks, bark, soil and even cars! Compared to other groups, lichens grow extremely slowly (from less than a millimetre to a few centimetres a year), but they seem to be extremely long-lived, with research indicating they can even survive for centuries.

Lichens are found nearly everywhere on Earth, in water, in deserts and from the poles to the tropics. The characteristics that allow them to thrive in extreme conditions are also responsible for their high sensitivity to pollution; lichens are excellent indicators of air quality. Some are used in toothpastes and others in medicine in treatments for skin diseases and respiratory conditions. Two species are found in perfumes, and others in dyes. In boreal areas they are a major food for caribou and reindeer.

Key to plate

1: ***Cora pavonia***
One of the few examples of a basidiolichen (lichen formed by a Basidiomycota mycobiont), and a 'cyanolichen', where the photobiont is a cyanobacterium instead of an alga, which can fix atmospheric nitrogen.

2: Bullseye lichen
Placopsis gelida
An example of a three-partnered symbiosis, where the fungus associates with two photobionts: a green alga embedded in the thallus and a nitrogen-fixing cyanobacterium, found inside separate structures called cephalodia (brown structure).

3: Shield lichen
Parmelia sulcata
While many lichens are highly sensitive to pollution, some, like *Parmelia sulcata*, can be very tolerant to sulphur dioxide.

4: Brown-eyed wolf lichen
Letharia columbiana
The common name 'brown eyes' refers to the sporing bodies (apothecia). Wolf lichens were used as poisons for wolves and foxes in Europe in the past. This species attaches to tree bark or wood.

5: Beard lichen
Usnea florida
A shrub-like lichen that often ends in flat discs (apothecia) shown here. *Usnea* species contain usnic acid, a potent antibiotic and antifungal agent. *Usnea florida* is very sensitive to sulphur dioxide air pollution.

6: Golden-eye lichen
Teloschistes chrysophthalmus
This shrubby lichen on twigs has bright orange apothecia surrounded by spiny projections (cilia). Its colour comes from the production of parietinic acid which destroys or inhibits growth of microorganisms.

7: Map lichen
Rhizocarpon geographicum
With flat and black apothecia and a yellow crust (resembling a map), this lichen grows on rocks at high elevations in areas of low pollution and is used in dating rock surfaces.

8: ***Tephromela atra***
A crustose species with black sporing bodies (apothecia).

9: British soldiers' lichen
Cladonia cristatella
Cladonia species produce two types of thallus – a small-lobed primary one and a secondary one, a stalked apothecium (podetium) containing algae with the spore-bearing hymenium at the tips (bright red in this case).

10: Umbrella basidiolichen
Lichenomphalia umbellifera
A rare example of a basidiolichen where the mycobiont is a mushroom. The algal cells are in squamules (small scale-like lobes) at the base.

11: Pin lichen
Calicium viride
This species produces its spores in a loose mass on top of a stalk, giving the appearance of dressmakers' pins.

Entomogenous Fungi

Entomogenous fungi, or entomopathogenic fungi, cause harm, infect, and may kill insects. Because they occur naturally in the environment, some are used as methods for safe pest control. For example, *Beauvaria bassiana* is used on termites, white flies, aphids and many other species that damage plants. The spores are mixed in a solution and then sprayed on the plants that are affected.

A particular group of these fungi, most belonging to the genus *Ophiocordyceps*, has become known as 'zombie fungi'. They can be found worldwide in both tropical and temperate regions. It is not known how many species there are, but many infect just one type of insect. These fungi release chemicals into insects' brains and take control of their bodies. Because most insects have nests below ground, the fungus makes them find higher places in plants and trees and then bite into a leaf or branch to anchor themselves there. After this, the fungus grows rapidly in the insect's body, creating sporing bodies. Being higher means the spores can be spread more widely.

Key to plate

1: Dong Chong Xia Cao
Ophiocordyceps sinensis
This fungus infects and kills caterpillars in the Himalayan regions of Nepal. It is used as a traditional medicine in China and has many different uses, including anti-diabetic and anti-inflammatory. Over time it has become rarer and very expensive. Due to overharvesting of the fungus it is endangered.

2: Weevil fungus
Ophiocordyceps curculionum
This fungus infects weevils (*Curculionidae*), from which it gets its species name. To date, these fungi have only been found in the tropical regions in South and Central America.

3: Wasp fungus
Ophiocordyceps humbertii
This *Ophiocordyceps* species, first discovered in the Atlantic rainforest of Brazil, infects wasps. It triggers the same kind of behaviour as the fungi that infect ants such as *Ophiocordyceps unilateralis* and *Pandora formicae*. The wasp lands on a branch or leaf and bites into it. The fungus then quickly grows out to produce sporing bodies.

4: Ant fungus
Pandora formicae
This species only infects wood ants and is found in large parts of Europe. When the fungus makes the ants sick, they walk away from the colony. Scientists are debating if the fungus is controlling the ants or if the ants are leaving their colony to protect it.

5: Zombie ant fungus
Ophiocordyceps unilateralis
This fungus releases chemicals into the brain of the ant, forcing it to walk up to a high branch. The fungus grows in the body of the ant and spores are dispersed widely because of its high position.

6: Caterpillar fungus
Cordyceps militaris
This fungus is found on caterpillars throughout the Northern Hemisphere.

7: White muscardine disease
Beauveria bassiana
Found worldwide growing naturally in the soil, this fungus infects insects and other arthropods giving them a white fluffy look. It is used as an insecticide to control insects such as termites, aphids and beetles.

Ants and Termites

The oldest farmers in the world are not humans, but ants and termites. While humans started growing their own food around 10,000 years ago, some species of ants and termites have been farming fungi for millions of years. These insects evolved separately from each other to cultivate their fungus food. Ants were the first farmers. Some 60 million years ago they were growing fungus in the Amazon rainforest of South America. Termites began around 30 million years ago in the tropical forests of Africa.

Even though both ants and termites grow a fungus for food, they do so in different ways. Every year at the same time that the termites build new nests, the *Termitomyces* fungus produces mushrooms on the termites' old nests. The termites collect spores released by the mushrooms when they crawl out of their new nests, and they use these to regrow their fungus gardens. Scientists call this 'horizontal transfer'.

Ants bring their fungus with them when they move home. When new ant queens leave their old nest, they take a little bit of fungus with them. The queens have a pouch inside their mouth, called the infrabuccal pocket, in which they can safely keep the fungus until their next nest is completed. Scientists call this 'vertical transfer' of the fungus. Mushrooms are not needed by the ants and are therefore a rare sight.

To grow their fungi, both ants and termites need to give it food to grow on. Leaf-cutting ants can be found walking in long lines through the rainforest with thousands of individuals carrying pieces of leaves. They collect these from trees and other plants. When they get back to their nest, they chew the leaves into little balls and give this to the fungus to grow on. In contrast, the termites dig long underground tunnels through which they carry dead grass and plant and tree material. They first eat this material themselves and grow the fungus on their own faeces.

Key to plate

1: Termite mushroom
Termitomyces striatus
These mushrooms grow from the fungus that the termites cultivate. Every season termites collect the spores coming from the mushrooms of old nests to build new fungus gardens. *Termitomyces* mushrooms are also a human delicacy.

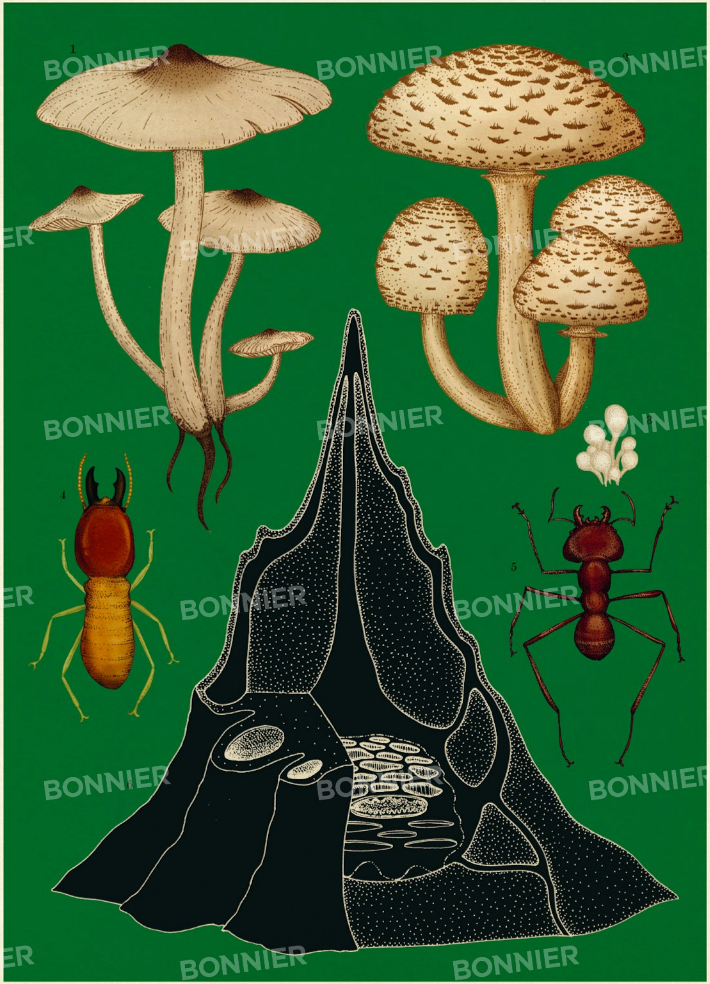
2: Ant mushroom
Leucoagaricus gongylophorus
Mushrooms from the ant fungus are a rare sight. They often appear when the ant colony is not doing very well. The ants do not like the mushrooms and try to remove them when they grow. It takes a lot of energy to make mushrooms, which are only grown to produce spores. Because the ants bring a piece of the fungus to build the new nests, spores are not needed. Mushrooms are therefore a waste of energy for the ants.

3: Ant food
Leucoagaricus gongylophorus
The fungus that the ants cultivate grows nutritious structures. These hyphal tips, called gongylidia, are swollen and packed with sugars and fats to feed the ants.

4: Fungus-growing termite
Macrotermes natalensis
Termites have big heads with strong jaws to protect themselves. You can find these termites throughout Africa and in Southeast Asia.

5: Leaf-cutting ant
Atta cephalotes
Leaf-cutting ants use their strong and big jaws (or mandibles) to cut the leaves they need to grow the fungus. They can also use these to protect themselves from dangerous predators.

6: Termite mound
Macrotermes natalensis
Termites are incredible architects. They build a big mound on top of their nest. With the chimneys in the mound, the termites can control the temperature, humidity and oxygen levels. The queen of the termites can be found safely in the middle of the nest in the 'royal chamber'.



FUNGARIUM

Gallery 4

Fungi and Humans

Early Mycologists
Plant Pathogens
Poisonous Fungi
Edible Fungi
Wonder Drugs
Ecosystem: Tropical Forests

Early Mycologists

The road to understanding the fungal kingdom has been long and arduous. In classical times it was believed that lightning strikes produced mushrooms, and even into the mid-eighteenth century, naturalists didn't understand fungi well. There were, however, small breakthroughs which began the process of defining fungi as mycologists understand them today.

The first person to really make progress was the Italian Pier Antonio Micheli (1679–1737), who was the first not only to describe and illustrate spores inside asci and on basidia (page 10), but to prove that spores could produce new fungi. But Micheli was too far ahead of his time and much of his work was never published. Regardless, his legacy is still alive today in names he coined including *Aspergillus*, *Clathrus*, *Mucor*, *Phallus*, *Polyporus* and *Puccinia*.

Carl Linnaeus (1707–1778), the 'father of modern taxonomy', actually set back the study of fungi rather than advanced it. His confusion around fungi led him to include them within the plant kingdom and he grouped together very different types of fungi under the same generic names.

Early mycologists also investigated organisms that we now know are not true fungi such as downy mildews and slime moulds, which are still named as true fungi. For example, Reverend Miles Joseph Berkeley (1803–1889), who was the founder of British mycology and whose fungal collection began Kew's Fungarium, shot to fame for his investigations into the cause of the potato blight – which led to the Great Famine in Ireland (1845–1849). Berkeley confirmed the cause was the organism we now know as *Phytophthora infestans,* a downy mildew. Arthur Lister (1830–1908) and his daughter Gulielma (1860–1949), spent some fifty years carefully observing and illustrating slime moulds, producing three editions of an exquisitely and lavishly illustrated book, *Monograph of the Mycetozoa*. Since these early observations, our understanding of the fungal kingdom has continued to evolve and now we have a better idea of what a fungus is (page 8).

Key to plate

1: Potato blight
Phytophthora infestans
a) Leaves and b) potato affected by symptoms
c) Sporangia with sporangiophores
We now know this and other so-called 'downy mildews' are in fact algae that lack the chloroplasts (organelles where photosynthesis takes place) characteristic of plants. They were thought to be a fungus as they can form filaments and spores similar to those of true fungi.

2: Slime moulds
Slime moulds do not share a common ancestor and belong mostly to a group called 'Amoebozoa.'
a) *Physarum polycephalum* in plasmodium stage: a single-celled branched network structure that looks for food and absorbs it. Even without a nervous system, these single-celled organisms seem to communicate collectively and learn about the substances they find. They form quickly when conditions are humid.
b) *Physarum* sporing structures
When conditions get dry the plasmodium turns into spore-bearing structures.
c) *Comatricha typhoides*
d) *Comatricha nigra*
e) *Leocarpus fragilis*
f) *Dictyostelium discoideum*
This grows well in culture in laboratory conditions and is used in genetics research.
g) *Hemitrichia calyculata*
Showing three stages of development

Plant Pathogens

Although most fungi perform helpful roles in recycling nutrients in ecosystems, some have adopted a different lifestyle that is harmful to the plants they interact with. Fungi that attack plants (fungal plant pathogens), are a major cause of crop damage, causing huge financial costs in agriculture and even threatening the supply of food to our tables. The price we pay for common food items in the shops is dependent on our success in our ongoing struggle with these fungi. It is estimated that 8–21 per cent of the six major food crops are lost to fungal pathogens and a further 10 per cent is lost after the crops are harvested.

New plant pathogens emerge on a regular basis, but our knowledge of their existence extends back to antiquity. A student of Aristotle, Theophrastus, provided one of the first written descriptions of fungal rust diseases. In the seventeenth century in Europe, farmers observed a connection between the presence of barberry plants growing on the margins of wheat fields and the levels of stem rust damage to wheat. This proved to be a valuable insight as barberry is now known to act as a host for the wheat stem rust *Puccinia graminis*. Digging up and destroying the barberry plants turned out to be an effective way of controlling the rust disease.

Fungi adopt three broad strategies to infecting plants. They can infect plants and live off their nutrients while keeping the plants alive (biotrophs), they can kill plants outright and digest the dead plant matter (necrotrophs) or they can start out as biotrophs but then switch to a necrotrophic lifestyle later. Infection begins when a fungal spore lands on a plant. Next, hyphae (page 16) emerge from the spore and spread across the surface of the leaf looking for a way in. Some fungi such as the rusts search out a natural opening – the stomatal pores which allow water in and out of a plant's leaves, for example. Others use a hardened hyphal tip to push through the leaf surface. Once they have gained entry, fungal pathogens interfere with the plant's ability to defend itself. For example, necrotrophic pathogens may release toxins to kill plant cells and then digest them. Biotrophic fungal pathogens keep infected tissue alive against the will of the plant which is trying to stop the infection.

Key to plate

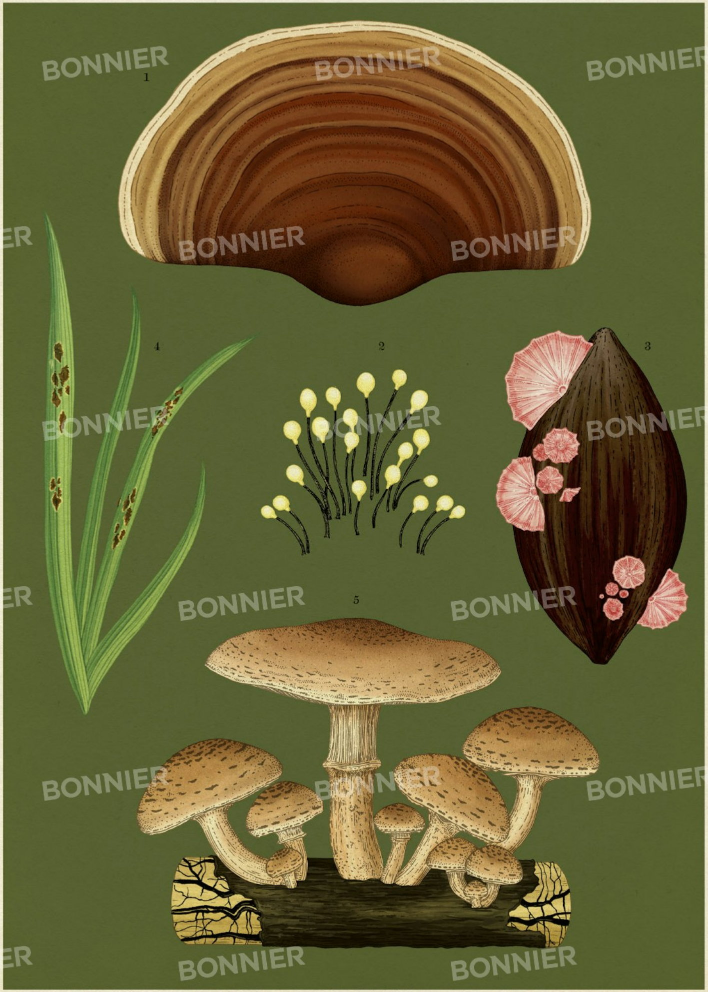
1: Basal stem rot
Ganoderma orbiforme
This fungus causes basal stem rot in oil palm plantations in Southeast Asia. The fungus produces woody brackets on the side of the infected tree.

2: Dutch elm disease
Ophiostoma novo-ulmi
This is a particularly aggressive cause of Dutch elm disease. It is spread by a bark beetle that lives in galleries inside the bark of the trees.

3: Witches' broom disease
Moniliophthora perniciosa
This pathogen infects cocoa trees, causing reduction in yield of up to 90 per cent. It is also resistant to fungicides.

4: Rice blast disease
Pyricularia oryzae
This infects rice plants, causing brownish lesions to appear on the leaves. It destroys enough rice a year to feed 60 million people.

5: Dark honey fungus
Armillaria ostoyae
Some honey fungi are major pathogens of trees and shrubs, forming black strands (rhizomorphs) which spread through the soil and split the bark from the wood. One colony of *Armillaria gallica* forms the 'humongous fungus' occupying 70 hectares of forest in Michigan State (United States). It is believed to be the largest organism on Earth.



Poisonous Fungi

Despite their reputation, few fungi are dangerously poisonous. Worldwide, only about 120 species out of 22,000 mushroom producing species are poisonous and of real concern; a mere 0.5 per cent. Another 90 species can cause stomach upsets in some people, and some 150 have hallucinogenic properties. In addition, there are some moulds that produce highly toxic compounds, including a *Fusarium* which has the potential to be used in biological warfare. Some of the mushrooms of most concern are common in temperate regions (page 32), and have close relatives which are edible but look very similar, and even belong to the same genus. Most instances of poisoning occur when a toxic mushroom is mistaken for its edible cousin, and great care must be taken when collecting mushrooms to eat. This mistake can cause nausea and vomiting or even a painful death. In Europe however, many instances of poisoning are in dogs that have eaten *Inocybe* species, notably *Inocybe geophylla* found on lawns.

In the case of *Amanita phalloides*, the toxins attack the liver and symptoms may not appear for a day or so after it is eaten. Equally unpleasant are the toxins in some orange species of webcaps (especially *Cortinarius orellanus*); the effects of the orellanine toxin can take over two weeks to appear and cause kidney failure requiring transplants to avoid death.

Particularly interesting is the effect of the substance ergotamine produced by *Claviceps* species, especially *Claviceps purpurea*, which appears in blackish, curved sword-like structures that sprout from the ears of cereals and other grasses. Ergotamine interferes with the nervous system causing hallucinations, itching and burning sensations; it also constricts blood vessels which can result in gangrene.

Fungi have evolved to produce an enormous range of chemical products, some of which are not toxic but highly beneficial to humans including cyclosporin, penicillins and statins (page 56). In most cases the role of these chemical products in nature is obscure, but it seems most likely that many serve to deter attacking insects, or as antibiotics which inhibit the growth of bacteria and parasitic microfungi.

Key to plate

1: Satan's bolete
Rubroboletus satanas
a) Exterior view
b) Interior view
So-called for its vibrant red stem and toxic nature, even consuming very small quantities of this fungus can lead to vomiting and dehydration. When cut or bruised, the flesh turns blue.

2: Kaentake
Trichoderma cornu-damae
This fatal species is found in parts of Asia and is considered one of the most toxic fungi in the world. Its distinctive red sporing bodies look similar to deer antlers.

3: Ergot fungus
Claviceps purpurea
a) Magnified view of sporing body
b) Ergots seen on rye
Ergot poisoning is one of the oldest known examples of fungal poisoning with records going back to at least 600 BCE. In Europe in the thirteenth to fourteenth centuries, when rye grass was a staple crop used in bread, poisonings often affected whole communities. Ergot's hallucinogenic properties were probably behind the behaviours that led to the 1692 Salem witch trials and executions.

4: Destroying angel
Amanita virosa
This deadly mushroom is found in woodland throughout Europe, and is evident in the summer and autumn months. Its sporing body is pure white.

5: Death cap
Amanita phalloides
Amongst the toxins involved in this deadly poisonous mushroom is an amanitin, which interrupts the most fundamental workings of cells by inhibiting a key enzyme which leads to cell death. This is a feature being researched for potential to attack cancer cells.

6: False morel
Gyromitra esculenta
The toxic false morel is named for its close resemblance to the edible true morel (page 54).

Edible Fungi

Humans have a long history of eating fungi. We know that mushrooms have been a food source since at least the Stone Age, but they were presumably eaten earlier. In ancient Rome, Caesar's mushroom (*Amanita caesarea*) was a delicacy of the emperors and in Sweden porcini (*Boletus edulis*) is known as Karl Johan's mushroom after King Karl XIV Johan, because he taught his people to enjoy this tasty food.

The reasons we eat certain mushroom species are often based on our cultures and traditions. For example, Europe can be divided into a mainly mycophobic (mushroom-fearing) western area where fungi are often seen as possibly poisonous, and into a mycophilic, (mushroom-loving) eastern and Mediterranean area where more species are eaten. Several peppery milkcaps (*Lactarius* spp.), for example, are commonly eaten in the eastern parts of Europe and Spain but are otherwise considered non-edible in the west.

Over the centuries we have learned by trial and error which fungi are edible. Occasionally a new understanding might come when studying fungi using modern scientific methods. The ugly milkcap (*Lactarius turpis*) was once considered an edible mushroom but is today known to contain a compound that causes genetic mutations.

The global market for edible mushrooms is worth about 32 billion pounds sterling a year, and includes both wild and cultivated mushrooms. Almost all cultivated species are decomposers, since they can be easily grown in dead organic matter, for example button mushrooms (*Agaricus bisporus*). However, many of the most flavoursome gourmet mushroom species, like porcini, are mycorrhizal which means that they live in a relationship with plants and are very hard to cultivate. There are some exceptions such as the black truffle, which grows underground and can be cultivated with oak trees (*Quercus*).

Globally at least 350 species of fungi are collected for food. The most commonly collected wild mushrooms are brittlegills (*Russula*), milkcaps (*Lactarius*), boletes (*Boletus*), agarics (*Amanita*) and chanterelles (*Cantharellus*).

Wild mushroom gatherers must be careful, however, since some edible mushrooms can cause allergic reactions in some individuals. Some mushrooms that are safe to eat also resemble poisonous species. It is also unsafe to collect food from polluted areas since heavy metals in soil can accumulate in mushrooms.

Key to plate

1: Matsutake
Tricholoma matsutake
Matsutake can be found in coniferous forests in Asia, Europe and North America. It is highly valued in Japan where it has been eaten for thousands of years.

2: Button mushroom
Agaricus bisporus
These are generally cultivated but are native to grasslands, especially in North America.

3: Chanterelle
Cantharellus cibarius
Chanterelle mushrooms are found in Europe. They are one of the easiest edible species to recognise.

4: Black truffle
Tuber melanosporum
The black truffle of southern Europe is one of the more expensive edible species in the world.

5: Caesar's mushroom
Amanita caesarea
Caesar's mushroom grows in southern Europe and North Africa (also page 8).

6: The true morel
Morchella esculenta
The true morel is common in Europe. It looks somewhat similar to the poisonous false morel, *Gyromitra esculenta* (page 52).

7: Baker's yeast
Saccharomyces cerevisiae
Baker's yeast was probably first isolated from the skins of grapes.

8: ***Penicillium roqueforti***
Constituent of blue cheeses, known to have been eaten by humans since 50 CE.

9: Zeller's bolete
Xerocomellus zelleri
This edible bolete is found in western North America.

10: ***Cabbage lungwort***
Lobaria linita
Several species of this lichen genus are used in soups and as medicines.

Wonder Drugs

Fungi are the source of some of the most important drugs ever discovered. Around the world, scientists research them in the hope of finding the next life-saving drug. The properties that make some fungi so useful in human medication may perform a useful role in the wild, for example inhibiting the growth of competitor bacteria. Some fungi have redefined what's possible with medicine, most famously, penicillin.

The story of penicillin starts in the London laboratory of the microbiologist Alexander Fleming in the 1920s. Fleming's Petri dish contained a culture of *Staphylococcus* bacteria but was also accidentally contaminated with the mould *Penicillium rubens*. Fleming noticed that the *Staphylococcus* could not grow near the mould and wondered if it was producing some kind of inhibitory chemical. Follow-up work by Howard Florey and his team at Oxford identified the inhibitory substance as penicillin and demonstrated its incredible powers for treating bacterial infections.

The realisation that infection could be treated so effectively with a chemical from a fungus, stimulated a worldwide hunt for fungi that produced other useful substances. One antibiotic discovered as a result was cephalosporine C, produced by *Acremonium chrysogenum*, which was isolated from a sewage outlet. A more recent discovery is the antifungal drug caspofungin, which comes from a chemical in *Glarea lozoyensis*.

Fungi have also proved to be a fantastic source of immunosuppressants – drugs that lower the response of the human immune system. Two important immunosuppressant compounds, cyclosporine and myriocin, come from fungi that grow inside insect larvae. These suppress the animals' immune systems but keep them alive as a source of nutrients. Cyclosporine made organ transplantation possible by preventing the immune system from rejecting the transplanted organ, while myriocin has been altered to produce a highly effective treatment for multiple sclerosis.

There are also the statin drugs whose founding member, lovastatin, was isolated from the mould *Aspergillus terreus*. The discovery of lovastatin has helped stimulate the development of the wider statin class that inhibit cholesterol synthesis and reduce the likelihood of cardiovascular disease. Discoveries such as this raise the obvious question; where will be the next fungal wonder drug be found?

Key to plate

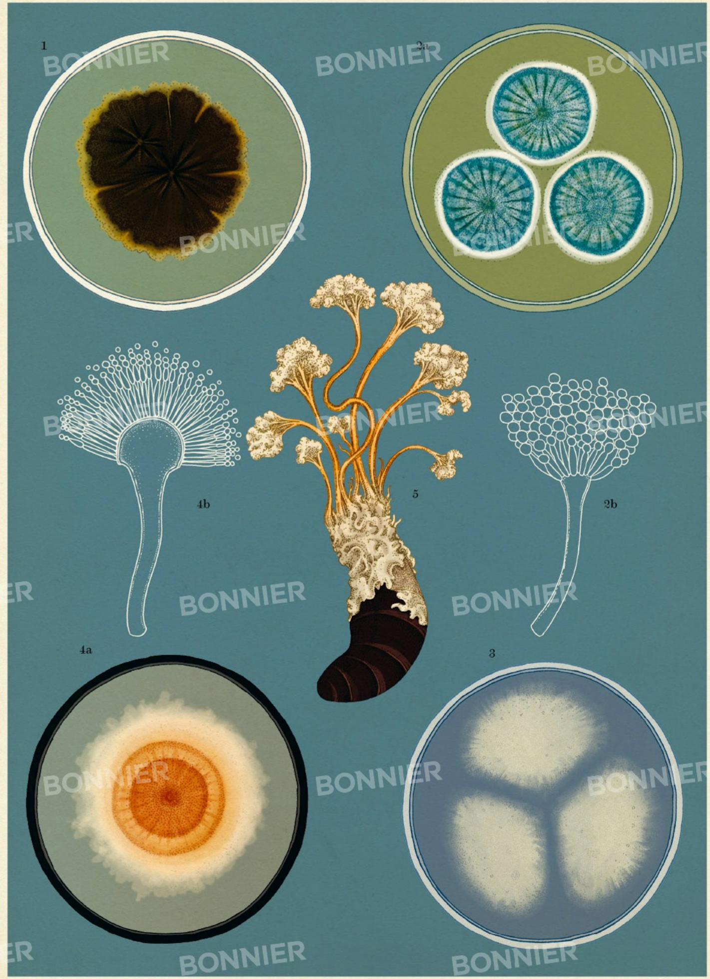
1: ***Glarea lozoyensis***
Colony seen growing on culture plate
This fungus was isolated from streams in the mountains of central Spain.

2: ***Penicillium rubens***
a) Colonies of *Penicillium rubens* growing on a culture plate
b) Appearance under light microscope

3: ***Tolypocladium inflatum***
The fungus is able to infect scarab beetles and produces the immunosuppressant compound cyclosporine, which is thought to help it evade the beetle's immune system. Cyclosporine can also suppress the human immune system and has revolutionised the field of organ transplantation. Previously, transplantations were generally unsuccessful as the organ was rejected by the recipient's immune system.

4: ***Aspergillus terreus***
a) Colony seen growing on culture plate
b) Appearance under light microscope
Aside from its effects in humans, lovastatin has antifungal properties suggesting its role in nature may involve deterring competitor fungi.

5: ***Isaria sinclairii***
Infected cicada nymph
This fungus produces the immunosuppressant compound myriocin. Like cyclosporine, myriocin is thought to help the fungus evade its host's immune system. Myriocin inspired the creation of a synthetic derivative called fingolimod which is a highly effective new treatment for the autoimmune disease multiple sclerosis.



Ecosystem: Tropical Forests

Step into a tropical rainforest and the first thing you notice (apart from the busy noise of insects) is its lush, diverse vegetation, with a myriad of leaf shapes and tree heights. The trees grow extremely densely with about 150–200 species per hectare compared to just 5–10 in temperate forests. Green all year round, they don't have marked seasons, so there is no autumnal flush of mushrooms. Instead fungi are seen sporadically throughout the year.

In contrast to boreal and temperate forests (pages 18 and 32), where the trees are almost always ectomycorrhizal (pages 36–39), those in tropical forests tend to associate with fewer species of endomycorrhizal fungi. This does not mean that tropical forests are species-poor in fungi. Scientists estimate that there are likely to be six to seven times as many fungi as plants growing in any one area. So, the tropics, with many more plants than temperate regions, are an amazing source of unexplored fungal diversity.

Leaves of many tropical trees live for several years, and develop a patchwork of specialised microscopic fungi, including lichen-forming species (page 30). Huge tree trunks can be covered by mosaics of shade-loving crustose lichens that partly live within the bark. Meanwhile, the vast quantities of wood and leaf litter that fall to the forest floor are broken down by fungi. One of the most visible in the tropics are the brightly coloured *Cookeina* species.

Tropical forests are enormously rich in insects, particularly beetles, some of which have minute fungi sticking out from their exoskeletons like tiny brushes, while their guts have been found to contain numerous yeasts which are new to science.

Key to plate

1: ***Pleurotus djamor***
This bracket fungus is saprotrophic, meaning it breaks down organic matter.

2: ***Letrouitia domingensis***

3: ***Deflexula subsimplex***
An example of coral fungus. This highly modified mushroom is shaped like worms and grows on trunks.

4: Christmas wreath lichen
Herpothallon rubrocinctum
This crust lichen grows on tree bark in shaded, moist forests in tropical and subtropical areas. Its common name is inspired by its concentric red and green bands.

5: Spotted cort
Cortinarius iodes
An ectomycorrhizal fungus that produces mushrooms with slimy purple caps and yellowish spots.

6: Amethyst deceiver
Laccaria amethystina
This mycorrhizal species can also be found in temperate regions.

7: Indigo milkcap
Lactarius indigo
As with all members of this genus, *Lactarius indigo* produces milk (or latex) when the mushroom is cut or broken. In this case, it is indigo blue.

8: Golden-scruffy collybia
Cyptotrama asprata
Appearing in all tropical regions, this saprotrophic fungus lives on branches and sticks.

9: Cobalt crust
Terana coerulea
The cobalt crust fungus appears as beautiful blue crusts on dead branches.

10: ***Pycnoporus sanguineus***
A bracket fungus, this is mostly found on dead wood in the Southern Hemisphere.

11: Pod parachute
Gymnopus montagnei

12: ***Cookeina speciosa***
(also page 22)

13: ***Lactocollybia aurantiaca***

14: ***Marasmius haematocephalus***

15: Parrot waxcap
Gliophorus psittacinus

FUNGARIUM

Library

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Curators

Katie Scott is illustrator of the bestselling *Animalium* and *Botanicum*, which was also produced in collaboration with the Royal Botanic Gardens, Kew. *Animalium* was chosen as the *Sunday Times* Children's Book of the Year, 2014. Katie studied illustration at the University of Brighton and is inspired by the elaborate paintings of Ernst Haeckel.

Ester Gaya is a senior research leader at Kew. She began her career in mycology in Spain and after some time in the USA decided to settle in the UK. She has spent the past 20 years researching fungi. She is especially fascinated by lichens and tries to understand their evolution.

David L. Hawksworth CBE has wide pure and applied mycological interests. He was the last Director of the International Mycological Institute, is an Honorary President of the International Mycological Association and an Honorary Research Associate of the Royal Botanic Gardens Kew.

Laura M. Suz is a research leader in mycology at Kew. She has spent almost twenty years digging up tree roots and looking at their ectomycorrhizas. Laura did her PhD in Spain on edible truffles. She moved to London in 2010 to investigate the fungi that associate with oak and the threats to their diversity.

Pepijn W. Kooij has studied fungus-farming ants for almost ten years in the hot tropics of Panama. Born in the Netherlands, he spent his visits to the zoo looking at leaf-cutting ants. He did his PhD in Denmark. In 2015, he moved to London to prove that it is not fungus-farming ants, but rather ants-farming fungi.

Kare Liimatainen is a Finnish mycologist with a PhD from the University of Helsinki who has also worked in Sweden and the United States. Working with colleagues he has found dozens of new fungal species in the UK over the last four years. His happiest memories are of trips to North America where the seasons were perfect and he was surrounded by masses of beautiful fungi.

Tom Prescott is a research leader at Kew. His work focuses on investigating the natural chemicals found in plants and fungi, with a special focus on their effects on human cells and the model fungal organism *Saccharomyces cerevisiae*. He also travels to Papua New Guinea to research the medicinal plants used by remote tribes.

Lee Davies comes from a palaeontology and invertebrate fossil background. After a stopover working on tropical African plants, he has become Kew's mycology curator. He lives nomadically in London, on a narrowboat.

To Learn More

Mycological Societies
British Lichen Society
http://www.britishlichensociety.org.uk/
British Mycological Society
https://www.britmycolsoc.org.uk
Fungus Conservation Trust
http://www.abfg.org/
International Association for Lichenology
http://www.lichenology.org
International Mycological Association
http://www.ima-mycology.org/

The Fifth Kingdom
An online version of Bryce Kendrick's popular mycology textbook with over 800 pictures and animations.
http://mycolog.com/fifthtoc.html

Species Fungorum
Coordinated by Kew, this initiative gives current names for fungal species. If you come across an unfamiliar name, this is the must-go-to site.
http://www.speciesfungorum.org/

Royal Botanic Gardens, Kew
Learn about Kew's global and collaborative scientific work, making an invaluable contribution to solving some of the biggest environmental challenges facing humanity. Kew houses the world's largest fungarium with over 1.25 million dried specimens from all over the world.
www.kew.org
www.kew.org/science-conservation
https://www.kew.org/science/collections-and-resources/collections/fungarium

State of the World's Fungi (2018)
Prepared by international scientists, published by Kew, numerous facts on many topics included in *Fungarium*.
https://stateoftheworldsfungi.org/

US National Fungus Collections
Held by the US Department of Agriculture including collections previously held by the Smithsonian Institution.
https://data.nal.usda.gov/dataset/us-national-fungus-collections

Westerdijk Fungal Biodiversity Institute Utrecht, The Netherlands
This institute maintains around 100,000 cultures of fungi and hosts the MycoBank database owned by the International Mycological Association.
http://www.westerdijkinstitute.nl
http://www.mycobank.org