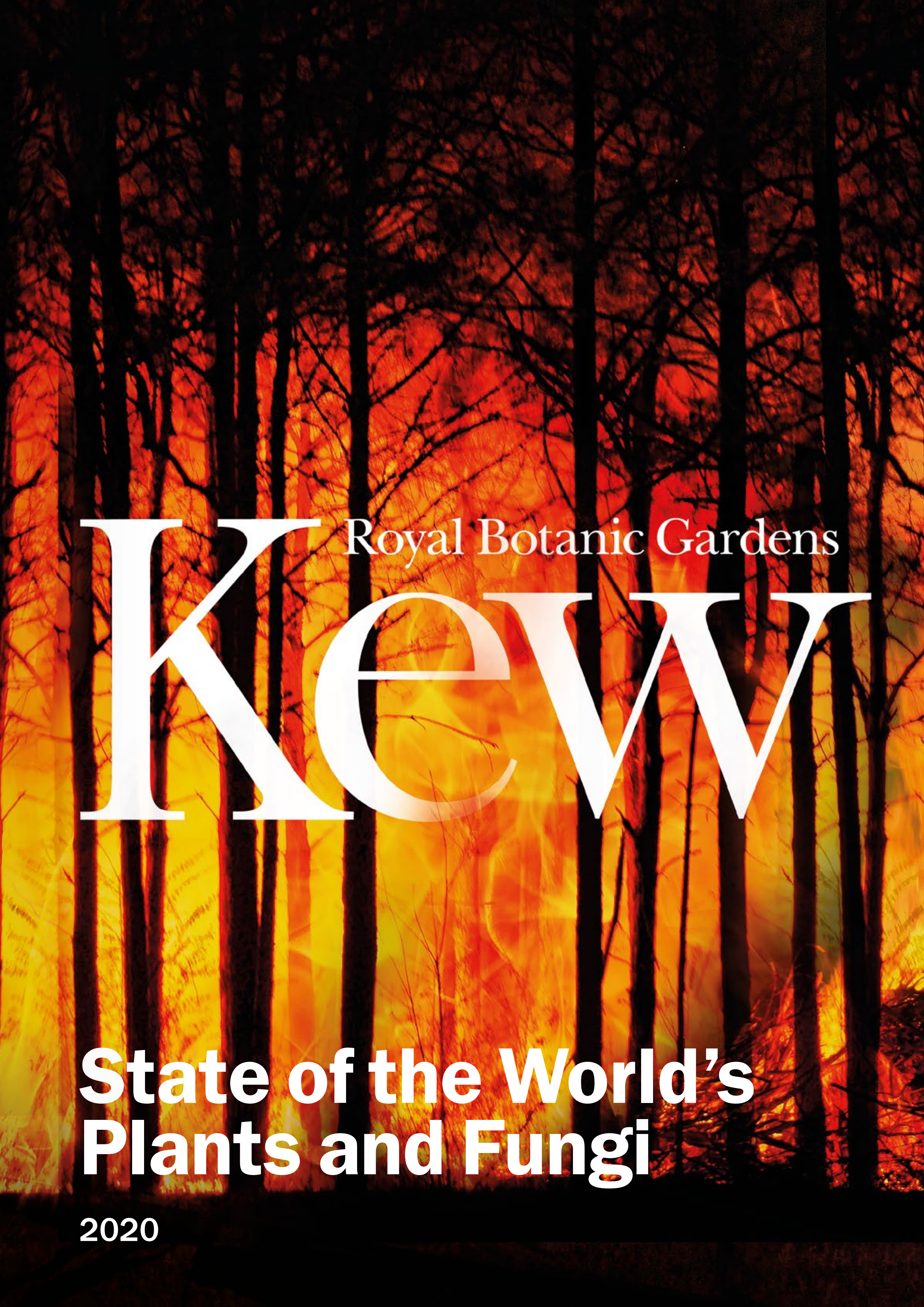


Royal Botanic Gardens Kew

State of the World's Plants and Fungi

2020

Contents

Introduction

Never before has the biosphere, the thin layer of life we call home, been under such intensive and urgent threat. Deforestation rates have soared as we have cleared land to feed ever-more people, global emissions are disrupting the climate system, new pathogens threaten our crops and our health, illegal trade has eradicated entire plant populations, and non-native species are outcompeting local floras. Biodiversity is being lost – locally, regionally and globally.

Yet this biodiversity sustains our lives. Open your fridge, peek into your medicine cupboard, examine your living room, feel your clothes. For thousands of years, we have searched nature to satisfy our hunger, cure our diseases, build our houses, and make our lives more comfortable. But our early exploration of useful traits in species relied on rudimentary tools, and indigenous knowledge was lost as local traditions were downplayed and globalisation emerged. As a result, humanity is still a long way from utilising the full potential of biodiversity, in particular plants and fungi, which play critical roles in ecosystems. Now, more than ever before, we need to explore the solutions they could provide to the global challenges we face.

New species are still being scientifically named and described each year, but, at the same time, others are moving towards extinction – losing the battle against the threats they face. A detailed understanding of these two sides of the coin is critical to conserving plants and fungi, along with the useful characteristics they hold. The responsible exploration of natural products, through advances in biotechnology and other techniques, will help us identify and utilise the useful features of plants and fungi to fight new diseases and deal with the emerging challenges facing our planet. Many species that are new to science are already known and used by people in the region of origin – people who have been their primary custodians and often hold unparalleled local knowledge. It is therefore critical that any benefits derived from those species primarily contribute to the well-being of those people.

This report tackles the knowledge gaps and unlocks the known and potential benefits of fungi and plants for us and our planet. Drawing upon the expertise of 210 researchers in 97 institutions across 42 countries, this unparalleled collaborative effort, generously funded by the Sfumato Foundation, aims to tell the world where we might find solutions to the challenges we face. Although there is no single or easy way out of the environmental crisis, the relevance of plant and fungal science cannot be understated.

This is the fourth report in Kew's *State of the World's* series, which focused on plants in 2016 and 2017, and fungi in 2018. This is the first time that plants and fungi have been combined in one report, to highlight their intrinsic links and joint benefits. It is also the first time that the report is accompanied by a full volume of expert-reviewed scientific publications in the New Phytologist Foundation's journal *Plants, People, Planet* (which can be accessed at https://nph.onlinelibrary.wiley.com/toc/25722611/2020/2/5). These freely accessible articles provide the references, background data, analyses and interpretations for this report, which has been written in a way that I hope you will find accessible and engaging.

In a publication that focuses on the sustainable uses of plants and fungi for humankind, it is important to state an obvious but increasingly forgotten aspect: that nature has a value of its own. We share this planet with millions of other species, many of which existed long before us. Despite the fact that an exploitative view of nature has deep roots in our society, most people today would agree that we have no moral right to obliterate a species – even if it has no immediate benefit to us. Ultimately, the protection of biodiversity needs to embrace our ethical duty of care for this planet as well as our own needs.

I hope you will share my enthusiasm for the findings presented in the next 12 chapters and that your appreciation for, and engagement with, fungi and plants will not be the same afterwards. Our challenges may be large, but as long as plants and fungi remain there is hope and opportunity.

Professor Alexandre Antonelli
Director of Science
Royal Botanic Gardens, Kew

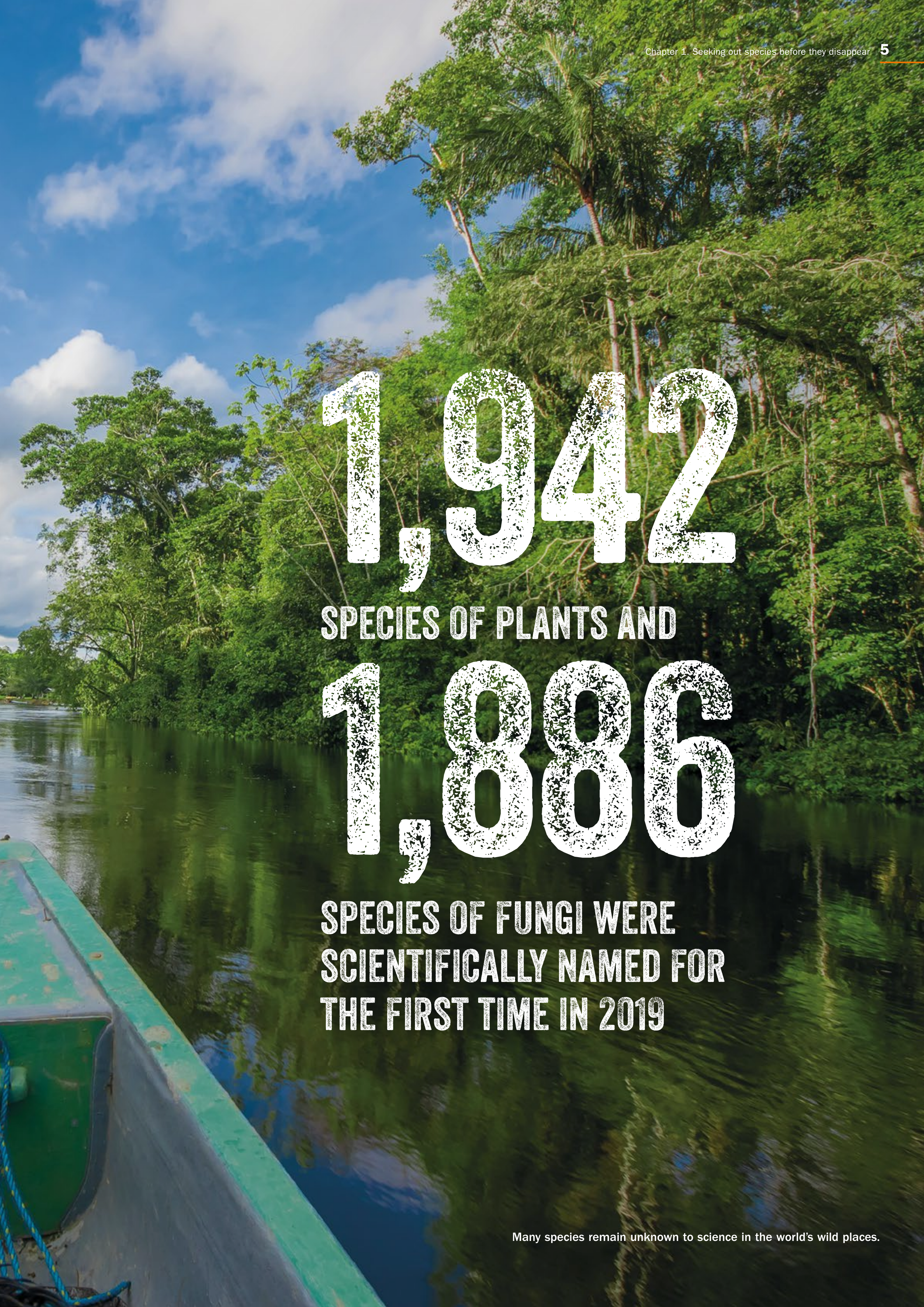
NOW, MORE THAN EVER BEFORE, WE NEED TO EXPLORE THE SOLUTIONS THAT PLANTS AND FUNGI COULD PROVIDE TO THE GLOBAL CHALLENGES WE FACE

IN AN UNPARALLELED INTERNATIONAL COLLABORATION, THIS REPORT DRAWS UPON THE EXPERTISE OF:

210 RESEARCHERS
IN 97 INSTITUTIONS
ACROSS 42 COUNTRIES

SEEKING OUT SPECIES BEFORE THEY DISAPPEAR

In this chapter, we find out: how exploration and detective work are revealing thousands of new species to science every year; which novel plants and fungi could yield new foods, timber and medicines; how a newly described fungus could help us save the banana; and why it took 160 years to name the bears' breeches *Barleria deserticola.*



1,942

SPECIES OF PLANTS AND

1,886

SPECIES OF FUNGI WERE SCIENTIFICALLY NAMED FOR THE FIRST TIME IN 2019

Many species remain unknown to science in the world's wild places.

Barleria deserticola

Galanthus bursanus

A small selection of the species named for the first time in 2019.

Naming *Barleria deserticola* was far from straightforward. First collected in Angola 160 years ago, it was not encountered again by a botanist until 2009. It took another decade to publish the scientific name and description.

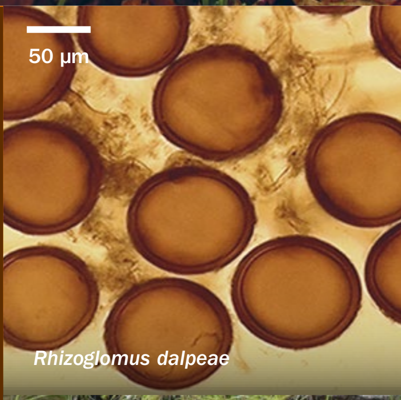
The snowdrop *Galanthus bursanus,* from north-west Turkey, was identified as a new species after a Ukrainian researcher spotted it in a holiday photo.

Scientists encountered *Rhizoglomus dalpeae* on an inselberg in Benin, West Africa.

Gladiolus mariae is only known to grow on two mountains in Guinea. The Kew scientist who encountered it in the wild named it after his wife.

The name of the fungus *Lecanora solaris* refers to the bright yellow ‘sunny’ colour of the fungus.

Cordyceps jakajanicola is a newly named fungal parasite of cicadas.



Rhizoglomus dalpeae

Gladiolus mariae

Cordyceps jakajanicola

Lecanora solaris

SCIENTISTS ARE CONSTANTLY ENCOUNTERING AND NAMING SPECIES OF PLANTS AND FUNGI THAT ARE NEW TO SCIENCE, MANY OF WHICH ARE ALREADY THREATENED. WITH BIODIVERSITY LOSS GATHERING PACE, WE NEED TO STEP UP THIS VITAL WORK OR RISK THE EXTINCTION OF MANY POTENTIALLY VALUABLE SPECIES.

Every year, as scientists explore the world's ecosystems, search herbaria and fungaria, sequence organisms' DNA and, increasingly, browse social media, they come across species of plants and fungi that have not been scientifically described. In 2019, botanists registered 1,942 newly named species of vascular plants on the International Plant Names Index (mainly flowering plants, ferns and gymnosperms). And mycologists recorded 1,886 novel fungi on the equivalent Index Fungorum.

Current threats to global biodiversity, from climate change, logging and land-use change, make the task of cataloguing species a race against time. Often, by the time a new species has been described and named, it is facing extinction. This means species that might be valuable as foods, medicines or fibres – or that play important roles in ecosystems, such as by helping to circulate nutrients – are disappearing before we've even had a chance to explore their characteristics.

"People often think that every species has been located and classified but it's not the case," says Dr Martin Cheek, Senior Research Leader on the Africa and Madagascar team at Kew. "There are still vast numbers of species on this planet that we know nothing about and don't even have names for. So that's the job we do in the Identification and Naming department at Kew. Once we have identified a species, the next step is to find out what its potential uses are, and whether it's a priority for conservation."

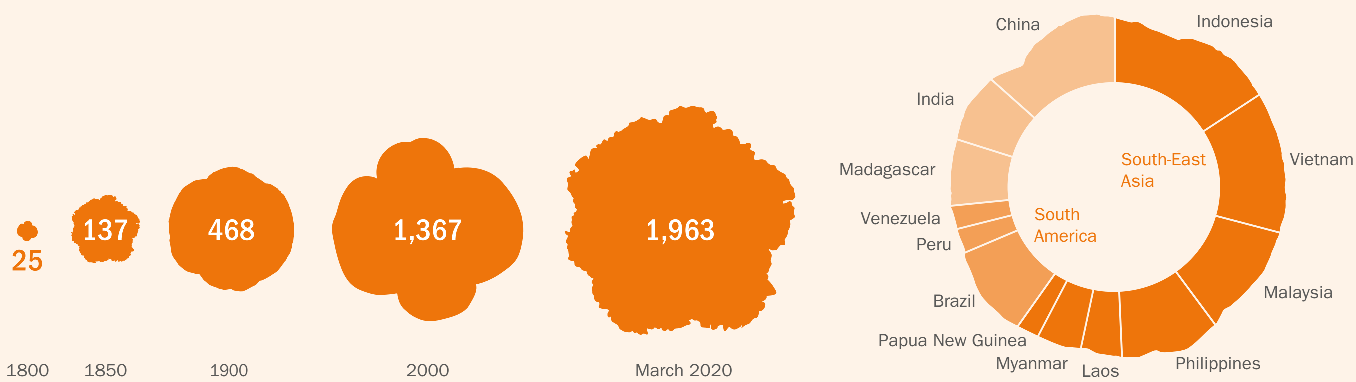
IDENTITY PARADE

Many of the plants described in 2019 have the potential to provide new drinks or foods. From China and mainland South-East Asia came 30 previously unnamed species of *Camellia*, the genus to which tea (*Camellia sinensis*) and many ornamental flowering shrubs belong. Meanwhile, six species of *Allium*, the genus that includes garlic, onions, leeks and chives, were encountered for the first time by scientists in Turkey, and ten undescribed spinach relatives from the genus *Chenopodium* came to light in California, USA. Brazil yielded two wild relatives of cassava *(Manihot esculenta)* that were previously unknown to science, as well as wild relatives of yams (*Dioscorea*) and sweet potatoes (*Ipomoea*).

"The manihots have the potential to be really important for future-proofing the cassava crop, which is a staple food for some 800 million people worldwide," says Dr Cheek.

FIGURE 1: Increase in the number of known species of *Begonia* since 1800

The rate at which new species of *Begonia* are being scientifically described has increased rapidly over the last two centuries. Between 2014 and 2019, an average of 60 new species of *Begonia* were published per year, making it one of the fastest-expanding genera. The pie chart shows where the 46 species of *Begonia* named in 2019 come from, mainly South-East Asia.



New begonias coming to our gardens soon?

Begonias are much-loved garden plants in the UK, but did you know they originate in tropical climes? The genus *Begonia* occurs throughout the tropics, with species mostly growing in undisturbed cloud and montane forests. Some are epiphytes (they grow on other plants, often trees), while others favour shady rock faces or waterfalls. To date (March 2020) 1,963 species have been named but botanists expect this figure to exceed 2,000 by the end of 2020. Some of these new species may one day make it into our gardens.

"The genes present in the newly named species might, for example, be useful in helping to make the current crop pest- or disease-resistant, or to enable it to grow in other habitats with different rainfall or soil fertility patterns."

Potential new medicines were also among the plants new to science. *Eryngium arenosum*, encountered by scientists in Texas, USA, comes from a genus containing plants used to treat inflammation, high blood sugar and scorpion stings; *Artemisia baxoiensis*, pinpointed in Tibet, is closely related to the antimalarial *Artemisia annua*; and three previously undescribed species, located far apart in Italy, Poland and on a Mexican Pacific island, are from the *Oenothera* genus. Also known as evening primrose, *Oenothera* species produce gamma linoleic acids used to treat systemic sclerosis, eczema and psoriasis.

The revelation to science of the tree *Cedrela domatifolia*, from the mahogany family (Meliaceae), might provide us with a new source of timber. And eight newly described species from the palm genus *Calamus*, found in South-East Asia and India, could, like their close relatives, supply rattan of value to the multibillion-dollar cane furniture trade. Meanwhile horticulturists are likely to be excited by 28 newly named species of tree fern, 46 novel *Begonia* species (see Figure 1) and the spectacular red-flowered *Gladiolus mariae*. Scientists encountered the gladiolus on an isolated mountain in Guinea, West Africa.

The fungal kingdom yielded species new to science, too: from mycorrhizal fungi that form mutualistic relationships with plants, to plant pathogens, animal-associated fungi and lichens. Among the mycorrhizal fungi, 51 came from the family containing milkcaps and brittlegills (Russulaceae). Mushrooms in this family form associations with plants that range from giant *Lithocarpus* trees in South-East Asia to dwarf willows (*Salix arctica*) in the Arctic. A further 37 species were newly described across 15 genera of the Boletaceae. These include eight species of the genus *Strobilomyces*, from which the edible 'old man in the woods' mushroom hails.

One of the most important fungus namings of 2019 was that of the species *Fusarium odoratissimum,* responsible for Panama disease of the Cavendish banana. This fungus had previously only been recognised as one of several *Fusarium oxysporum* strains, or genetic variants. The species began to spread in Cavendish plantations across Asia in the 1990s, later arriving in Africa, the Indian subcontinent and the Middle East. It is now also gaining ground in South America. Some 116 million tonnes of bananas are grown every year, with Cavendish accounting for 40–50% of global production.

"*Fusarium odoratissimum* did not have an official name before, and there had been no proper study of the species limits within the complex," explains Dr Tuula Niskanen, Research Leader in Mycology at Kew. "However, several species have now been identified, and finally we have a name for the one that is currently threatening the global production of the Cavendish banana. That means we now have a better way to communicate information about this disease and target research. It's good to know our enemies, because once we know them, we can find better ways to control them."

Some fungi live in symbiotic associations with photosynthetic partners (algae, cyanobacteria, or both) forming lichens. In 2019, more than 200 species of 'lichenised' fungi from 37 families and 87 genera were named scientifically. Mycologists came across them in all kinds of environments, from high-altitude tea plantations in Sri Lanka to Ecuador's Galapagos Islands and dry tropical forests in Mexico. Demonstrating the value of citizen science to taxonomy, *Allographa kamojangensis* was only identified from Indonesia after a photo of it was posted on the Facebook group 'Lichens Connecting People'.

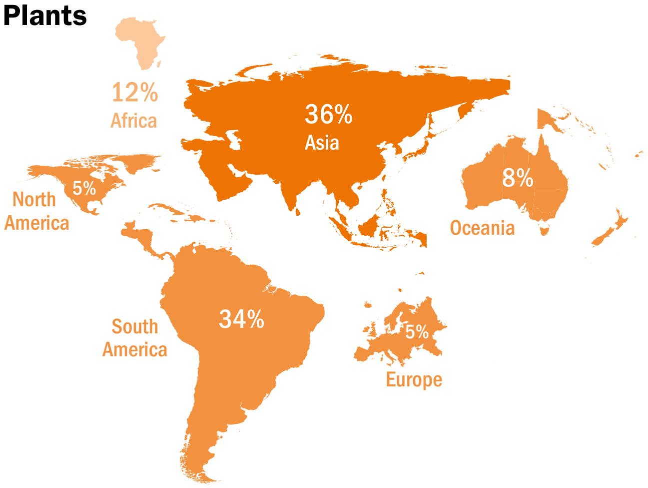
REVEALING BIODIVERSITY

Current rates of new plant descriptions are likely to continue. The World Checklist of Vascular Plants, the most comprehensive and regularly updated species list of its kind, records around 350,000 accepted species, of which 325,000 are flowering plants. Ten years ago, scientists thought that the vast majority of flowering plants had been described and named. But the subsequent stream of species revealed to science suggests there are many more to find, as do the experiences of botanists undertaking fieldwork in the tropics today.

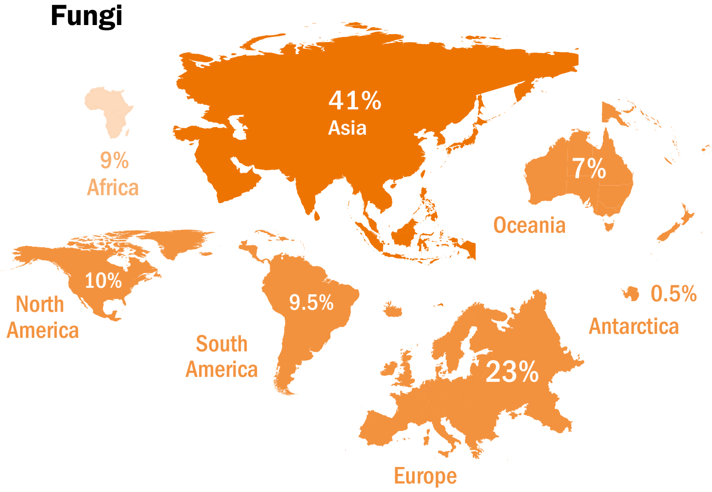
FIGURE 2: The proportion of species from each continent named as new to science in 2019

The relative size of the continents reflects the number of species named from each. There were no plants named from Antarctica.

Plants



Fungi



When it comes to fungi, we have even more left to catalogue. Currently, 148,000 species have been identified, primarily in the Ascomycota and Basidiomycota phyla. But scientists believe that more than 90% of species remain unknown to science. They estimate that there are between 2.2 to 3.8 million species on Earth. The main reason we know so little about fungi is because they lead very cryptic lifestyles. Whereas almost all plants are visible above ground, fungi often remain concealed.

"The study of fungi is mainly based on their spore-bearing structures, including the mushrooms that we see above ground, and many species only produce them at certain times of the year," explains Dr Niskanen. "Some species don't even produce them every year – perhaps only every ten years – and some species don't produce them at all. The species we know best are those that produce mushrooms. Those that don't produce any visible spore-bearing structures are thus the least known so far."

HOTSPOTS FOR UNNAMED SPECIES

Between the 1990s and 2018, three countries consistently yielded the highest numbers of newly described species of plants: Brazil, China and Australia. However, in 2019, Australia (with 86 newly described species) was knocked out of the top three by both Colombia (121) and Ecuador (91). Brazil retained the number one spot (216), which it has held since 2008. Every year, 200 or more new species are described from Brazil, equating to 10% of the global total. China took second place (195) in 2019.

The dominance of Brazil, China and Australia is likely connected to the fact that all have rich treasure troves of biodiversity and large numbers of professional taxonomists. On the other hand, the Democratic Republic of Congo yielded only seven new species descriptions, despite being tropical Africa's largest country and home to many species-rich habitats. This likely reflects the lack of taxonomists, scientific infrastructure and security, as well as periodic hazards such as outbreaks of the Ebola virus.

Northern temperate and boreal countries yield very few novel plants these days, being far less diverse than the tropics and having been very well surveyed over the years. When it comes to fungi, however, species that are new to science can still be found almost anywhere, their locations reflecting areas with the most research activity. In 2019, most newly named species of fungi came from Asia (41%) and Europe (23%), with nine from the UK. At the other end of the scale, Antarctica yielded 0.5% of the fungal scientific novelties (see Figure 2).

WE CAN'T ASSESS HOW THREATENED A SPECIES IS UNTIL WE KNOW IT EXISTS. THIS MAKES LOCATING, DESCRIBING AND NAMING SPECIES A CRITICAL TASK

Describing and naming a new species to science can take time. For plants, the vast majority are described using morphology alone, in other words, on the basis of their flowers, fruits, leaves and other parts. First, a scientist has to collect a specimen of a plant suspected as being unknown to science to deposit in a herbarium; then they must compare it to reference specimens of similar species to ensure the find has not, in fact, already been described. Finally, they have to choose a name and publish its characteristics in the scientific literature. This process can be protracted – *Barleria deserticola* was first collected 160 years ago, but only encountered again in 2009 and not given a formal scientific name until 2019.

Advances in DNA technology have helped to speed up the naming of species in recent years, particularly for fungi. Unlike for plants, a single DNA marker known as the 'internal transcribed spacer', or ITS, is often able to distinguish many fungi to species level. The new techniques have also revealed many species new to science from environmental samples, for example from soils. However, one of the problems associated with DNA-based methods of description is that for a fungus to be officially named by the scientific community as a new species, it is customary to have a reference specimen in a fungarium. "The idea is to have something that is physical so people can go back and do more studies of the species if needed," says Dr Niskanen. "However, for fungi that don't, for example, produce mushrooms, or can't be cultivated, you don't really have anything you can put in a fungarium. An alternative could be storing a soil or DNA sample that would contain the genome of the species."

SAFEGUARDING SPECIES

The United Nations' Sustainable Development Goal 15 calls for the protection of terrestrial ecosystems and halting of biodiversity loss. Programmes to conserve species identified as threatened through extinction risk assessments (such as those of the International Union for Conservation of Nature Red List of Threatened Species) provide a route to achieving this. However, we can't assess how threatened a species is until we know it exists. This makes locating, describing and naming species a critical task if we are to conserve plants and fungi for future generations.

This chapter is based on the following scientific paper published in *Plants, People, Planet*, where you can find more information and references: Cheek et al. (2020). New scientific discoveries: Plants and fungi. *Plants, People, Planet* 2(5). DOI: https://doi.org/10.1002/ppp3.10148

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Read Chapter 2 to learn how our understanding of extinction is changing and how this is informing conservation efforts.

CALCULATING EXTINCTION RISK FOR PLANTS AND FUNGI

In this chapter, we explore: how scientists work out which species may go extinct; why they are adopting statistical methods used by election pollsters; different ways to evaluate losses from extinction; why species that seem to be thriving may be doomed; and how Artificial Intelligence is helping us identify which species to conserve.

Human activities are accelerating biodiversity loss.

UNDERSTANDING WHICH PLANTS AND FUNGI ARE THREATENED IS VITAL TO HALTING BIODIVERSITY LOSS AND MINIMISING FUTURE EXTINCTIONS. NEW TOOLS AND APPROACHES ARE HELPING US IMPROVE HOW WE SET CONSERVATION PRIORITIES.

Natural ecosystems provide useful services for humanity, such as regulating climate, preventing floods and filtering water. As the building blocks of ecosystems, plants and fungi have the potential to help us address current environmental challenges, such as climate change. However, these natural benefits could be compromised by biodiversity loss, caused by humans clearing or degrading natural vegetation and over-harvesting wild species, as well as by shifting weather patterns.

If we are to protect the world's plants and fungi – part of our 'natural capital' – we need to understand the threats they face and whether they are at risk of extinction. This involves assessing the conservation status of species, including identifying biases and gaps in our knowledge. "It's important to have a clear idea of which plants and fungi are at risk where, because that information should inform every new development and every conservation action," says Dr Eimear Nic Lughadha, Senior Research Leader in the Conservation Science department at Kew.

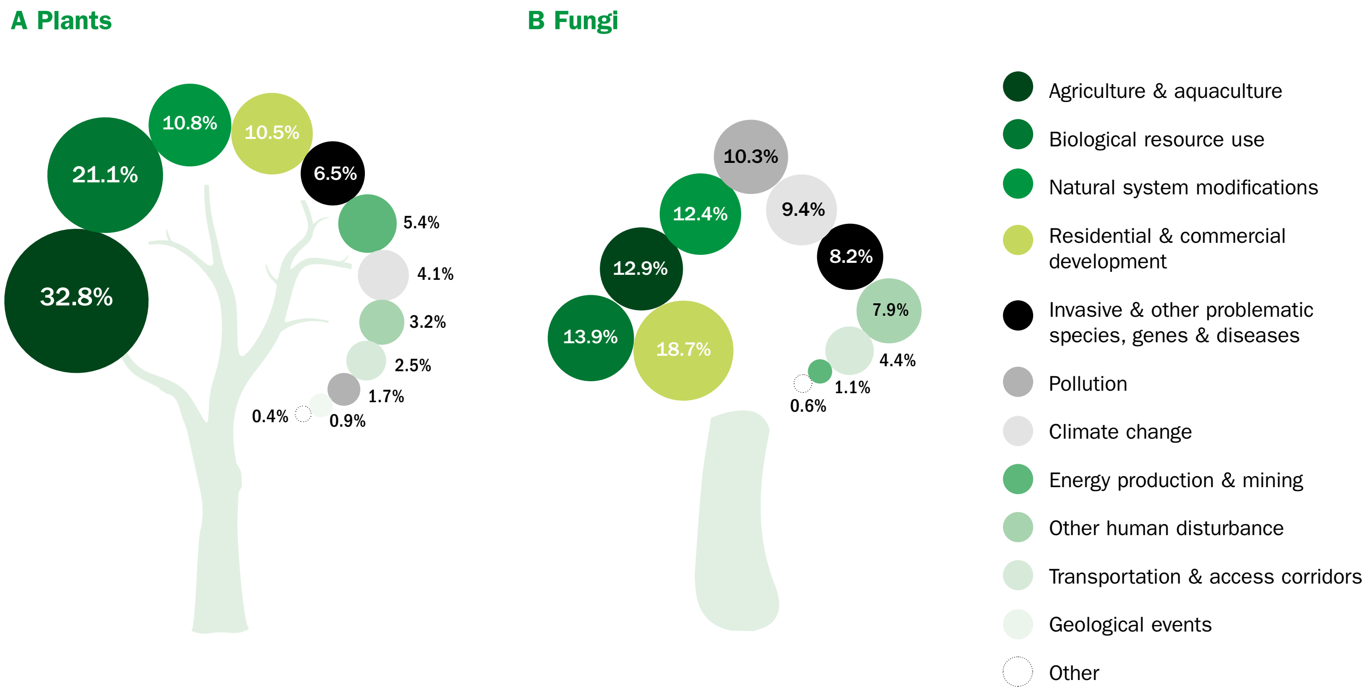
The International Union for Conservation of Nature (IUCN) Red List of Threatened Species is the global gold standard for assessing species' extinction risk to inform priority conservation actions. Assessments are conducted using five criteria, including geographic range and population size. Together with threats (see Figure 1), these determine the category to which a particular species is assigned: Extinct, Extinct in the Wild, Critically Endangered, Endangered, Vulnerable, Near Threatened, Least Concern or Data Deficient.

Such assessments are a powerful tool for supporting conservation policy, planning and action. They help authorities to delineate protected areas, guide allocation of funding and influence development decisions. For example, the International Finance Corporation (World Bank Group) requires clients to use the global Red List to avoid activities that would reduce populations of Critically Endangered or Endangered species.

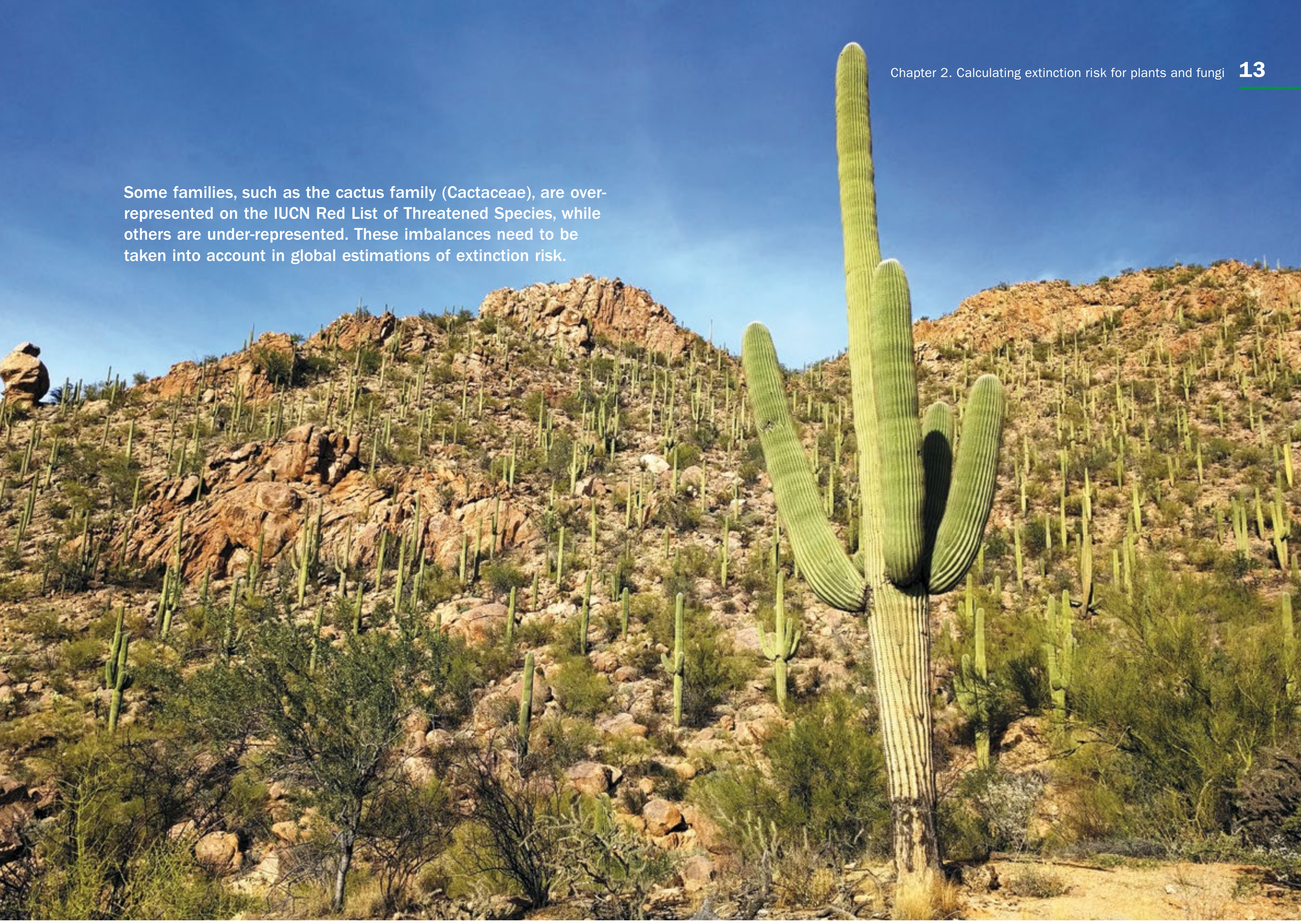
Although the Red List is the most comprehensive source on global extinction risk for species, just 116,177* of the 2.1 million or so known species of plants, fungi and animals are represented on it – approximately 6% (see Box 1, over page). Plant coverage was boosted to 10% by the addition of 19,000 conservation assessments between 2017 and 2019, but coverage of fungi is far lower. A mere 285 of 148,000 described fungal species are assessed on the Red List, equating to 0.2%. As Chapter 1 explained, many more species of plants and fungi have yet to be scientifically described (estimates suggest at least two million), and these will also require assessments.

FIGURE 1: Why species are at risk

The major threats to plants (A) and fungi (B) that have been assessed for the IUCN Red List of Threatened Species.



*The research described in this chapter was based on the IUCN Red List of Threatened Species 2020.1, current at the time. In the most recent IUCN Red List update (2020.2), this figure has increased to 120,372.



Some families, such as the cactus family (Cactaceae), are over-represented on the IUCN Red List of Threatened Species, while others are under-represented. These imbalances need to be taken into account in global estimations of extinction risk.

"We are progressing rapidly but there are two traps that we need to avoid," says Dr Nic Lughadha. "The first trap is thinking that an individual species assessment tells us everything we need to know about that species' risk of extinction. And the second trap is thinking that the subset of species that have been assessed, and the stats around them, tell us everything we need to know about the risk to plants and fungi globally."

ADDRESSING BIAS

Plants on the Red List are not collectively representative of the global situation because multiple motivations have driven how species have been selected for assessment on the list. These include: the availability of information; human interest in useful, attractive or unusual species; national assessment initiatives; and a focus on assessing species or groups suspected to be exceptionally threatened. In addition, there are well-documented geographic, taxonomic and temporal gaps and biases.

Comparison with comprehensive lists of all vascular plants and those with recorded uses enabled an international team of researchers led by Kew to quantify some of these biases. The work revealed that plants from tropical Asia are under-represented on the Red List, while those from Africa are over-represented. Some of the most species-rich families are among the most under-represented, including the daisy, orchid, grass and mint families (Asteraceae, Orchidaceae, Poaceae and Lamiaceae, respectively). Together, these comprise almost a quarter of all vascular plants.

Meanwhile, the Red List over-represents families targeted by assessment programmes, such as the cactus family (Cactaceae) and the myrtle family (Myrtaceae).

Polling companies face a similar challenge with data biases during political elections. "Their problem is that the people who answer the phone or respond to an online poll are not a representative sample of all registered voters," explains Dr Barnaby Walker, Conservation Science Analyst at Kew. "However, the pollsters have access to demographic data too, which lets them see additional attributes of those registered to vote by local area, such as age and qualifications. This allows them to adjust their forecasts to correct for the bias in the sample of voters who responded to their polls."

Dr Walker and colleagues applied the same statistical modelling method used by some pollsters – called multilevel regression and post-stratification – to correct for certain biases in the global Red List data. Accounting for under- and over-represented groups and areas enabled the scientists to infer extinction risk more accurately. The model predicted the overall proportion of threatened species to be 39.4%, slightly lower than the 43.7% of vascular plants assessed for the Red List that are considered threatened. They found the threat levels of the myrtle, laurel, beech and sedge families (Myrtaceae, Lauraceae, Fagaceae and Cyperaceae, respectively) to be among the most underestimated, with those of the ebony (Ebenaceae) and palm (Arecaceae) families among the most overestimated. In general, threat levels are underestimated for plants across large parts of the Americas. These findings can be used to guide future assessment priorities.

As well as estimating extinction risk, it is important to understand how the risk of extinction is changing over time. To identify trends in extinction risk, scientists developed the global Red List Index (RLI). The index value is updated as species are reassessed, tracking genuine changes in extinction risk for an entire group. This index can monitor progress towards achieving global biodiversity targets. Since plant coverage on the Red List is incomplete and biased, a sampled approach is used, with species drawn at random to represent the geographical and taxonomic breadth of plants globally.

As part of ongoing efforts to determine a global RLI trend for plants, the research team re-analysed the extinction risk of 400 species of monocots (plants with only one seed leaf, for example grasses, orchids, palms and sedges) and legumes (members of the pea family: Fabaceae) occurring in the mega-diverse countries of Brazil and Madagascar. These relatively well-known groups were chosen as a proxy for overall plant diversity. A decreasing RLI value indicates that species are moving towards extinction. The study found that there was a slight decrease in RLI for monocots and legumes overall, with no significant change for Brazil, and the steepest downward trend in Madagascar. Repeating conservation assessments over time can reveal trends and enable comparison between different groups of organisms (see Figure 2).

While conservation risk assessments and trends are helpful for understanding the status of, and threats to, plants and fungi, they only show part of the picture. Extinction results not only in the loss of a particular species, it also wipes out the unique evolutionary history that the species represents, including irreplaceable features and unique combinations of functions, some of which could be beneficial to humans. If a species is the sole survivor of an old lineage on the 'tree of life', its loss will eradicate greater evolutionary history than if it recently evolved and has several close relatives.

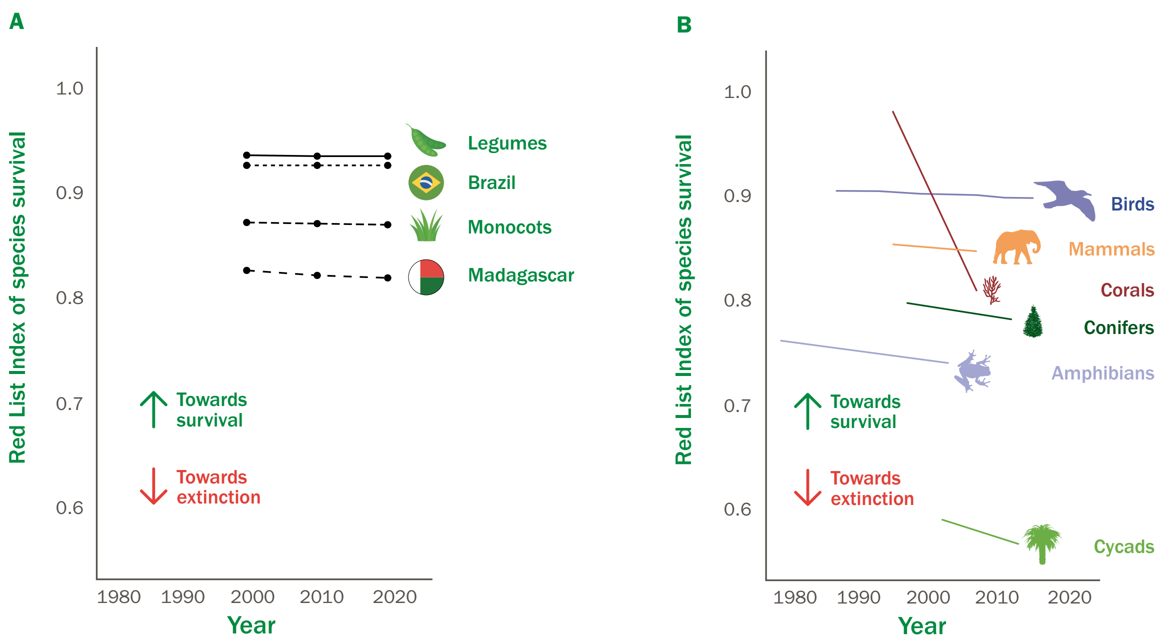
Take the genus *Ginkgo*, for example, which is the only remaining genus in the order Ginkgoales. The sole surviving species of this group is *Ginkgo biloba,* now isolated in the tree of life on a long branch representing hundreds of millions of years of unique evolutionary history. Today, *Ginkgo biloba* only grows in the wild in China, in a few isolated populations, but it is widely grown in gardens and parks around the world. "If *Ginkgo biloba* went extinct, we'd lose all that evolutionary history back to where the species branches off the main tree of life," says Dr Félix Forest, Senior Research Leader in Analytical Methods at Kew.

The loss of evolutionary history can reduce the likelihood that a group of organisms will contain enough diversity for its species to adapt to future changes. There is, therefore, a growing focus on encompassing plant evolutionary history when planning conservation priorities. The 'Evolutionarily Distinct and Globally Endangered' (EDGE) approach involves combining a species' extinction risk, deduced from a conservation assessment, with its evolutionary distinctness, determined from its position on the tree of life and the number of close relatives it has.

While widely used in the animal kingdom, this method has only been applied to a few plant groups – and no fungi – to date. This is because it requires comprehensive knowledge of the relevant portion of each kingdom's tree of life.

FIGURE 2: Quantifying extinction risk trends

A) The Red List Index (RLI) of species survival for sample species of monocots and legumes from Brazil and Madagascar. RLI = 1.0 equates to all species being of Least Concern conservation status; RLI = 0 is the equivalent of all species being Extinct. As the graph indicates, monocots are more threatened than legumes, and species occurring in Madagascar are more threatened than those in Brazil.
B) RLI of species survival trends depicted for various other plant and animal groups.

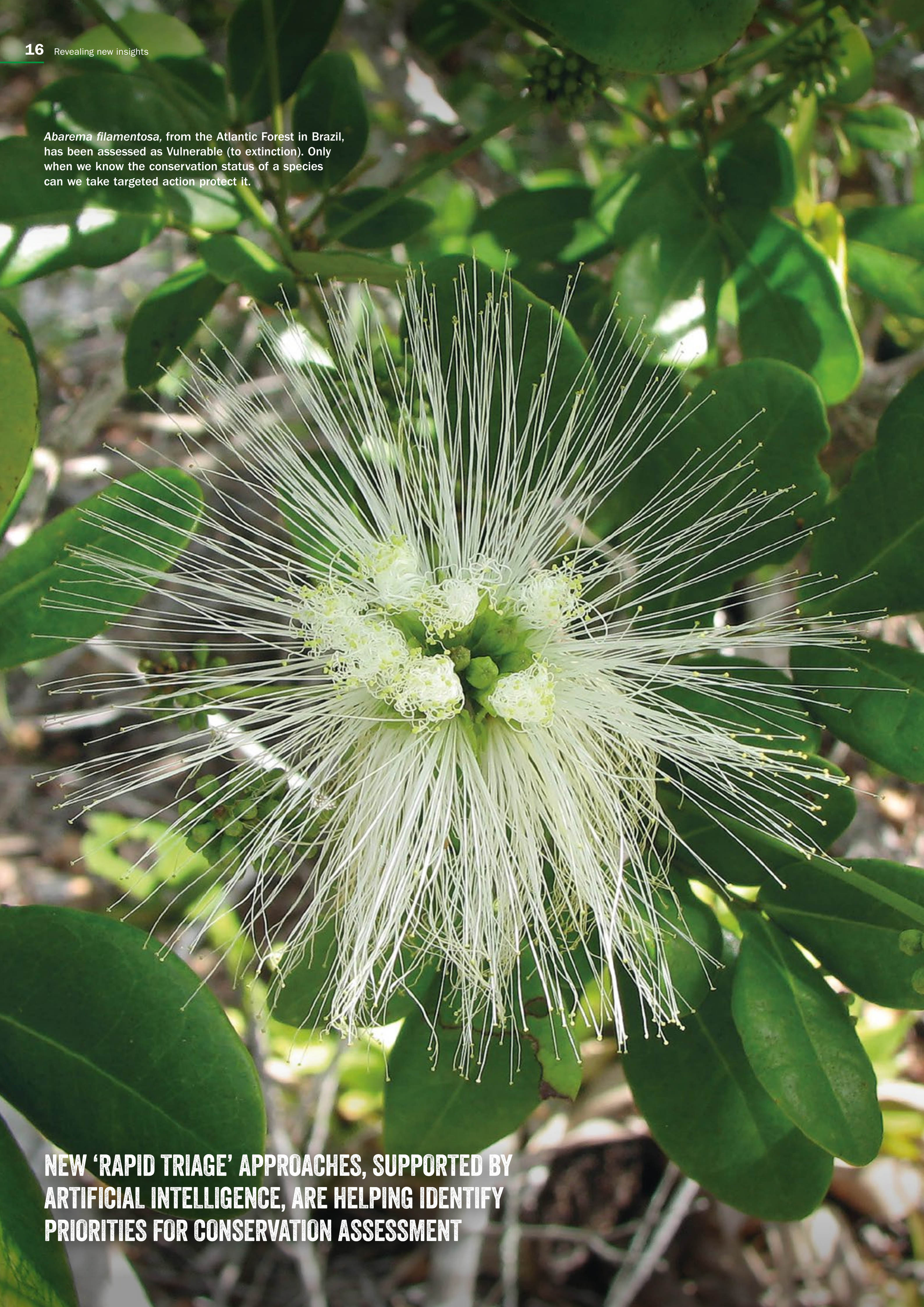


If the maidenhair tree (*Ginkgo biloba*) goes extinct, we will lose hundreds of millions of years of evolutionary history.

BOX 1: Global progress in assessing plant and fungal extinction risk

In response to global targets set by the Convention on Biological Diversity, botanists and mycologists face the challenge of assessing the status of all plants and fungi. The large number of species yet to be described is adding to the challenge. “Fieldwork in understudied regions and habitats, along with taxonomic revisions and DNA-based environmental sampling, are all revealing new species,” said Prof. Gregory Mueller, Chief Scientist and Negaunee Vice President of Science at Chicago Botanic Garden, part of the team that carried out the research described in this chapter. “These new discoveries exacerbate the challenge of assessing the conservation status of all species to enable appropriate conservation action.”

For plants, the collective assessment efforts of thousands of experts are compiled in the ThreatSearch database managed by Botanic Gardens Conservation International. ThreatSearch now contains global assessments for around 30% of plant species. However, these include assessments using a variety of systems and standards. For a more consistent approach, scientists use the IUCN Red List of Threatened Species; the IUCN plant assessments are also indexed in ThreatSearch – making ThreatSearch the ‘one-stop shop’ for plant assessments. No similar resource is yet available for fungi.

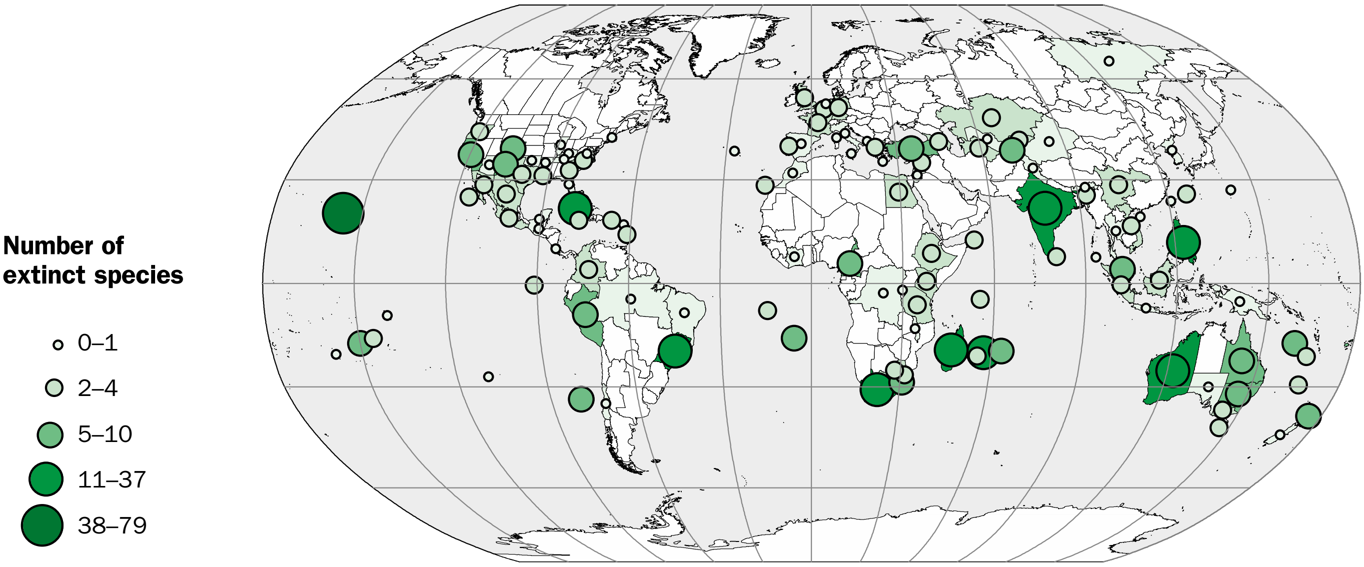


Abarema filamentosa, from the Atlantic Forest in Brazil, has been assessed as Vulnerable (to extinction). Only when we know the conservation status of a species can we take targeted action protect it.

NEW 'RAPID TRIAGE' APPROACHES, SUPPORTED BY ARTIFICIAL INTELLIGENCE, ARE HELPING IDENTIFY PRIORITIES FOR CONSERVATION ASSESSMENT

FIGURE 3: The number and distribution of modern extinctions

The number of recorded modern extinctions for plants, by country or state (the true number is likely to be far higher). The ongoing rate of plant extinctions is up to 500 times the pre-Anthropocene background extinction rate for plants, with some islands particularly badly affected (see also Chapter 12).



Scientists at Kew are currently tackling the challenge of obtaining genome-scale data for at least one genus of all 14,000 flowering plant genera and all 8,200 fungal genera under its Plant and Fungal Trees of Life Project. Automating the analysis of these trees of life, and using the EDGE approach, could provide a powerful tool for monitoring the changing threat to biodiversity over time.

ALREADY LOST?

Scientists are also exploring the concept of extinction debt. A direct relationship exists between the size of an ecosystem and the number of species it contains: the species–area relationship. This dictates that when an ecosystem such as a forest or wetland shrinks, species loss follows. However, the reported 600 modern plant extinctions (see Figure 3) are far fewer than would be expected from observed habitat loss. This is because extinctions are delayed. After habitat is lost, the area continues to support a similar number of species until the surplus – the extinction debt – is lost through a process of 'relaxation' and a new equilibrium established matching the species–area relationship.

"Imagine a sudden disaster destroying 90% of a forest," says Prof. John Halley, Professor of Ecology at Greece's University of Ioannina, who was part of the Kew-led research team. "While some plants will go locally extinct immediately, most species will still occur in the 10% that remains. However, the reduced area means that some, especially species that were rare anyway, will now be permanently exposed to dangerously low population levels. So, a proportion of the plants we can see growing now, and which we may think are fine, are in fact in a game of Russian roulette against the environment to get from one generation to the next. Extinction is postponed but not avoided."

If we are to conserve plants and fungi before they go extinct, experience suggests we do not have time to conduct a full conservation assessment for every species. However, new 'rapid triage' approaches, supported by Artificial Intelligence (AI), are helping to identify priorities for assessment. In addition, open-access resources that automate certain Red List assessment tasks are widening access, helping to speed up and standardise the process. And citizen science and remote-sensing observations have the potential to help keep extinction assessments up to date.

"We need to have a rough idea of the conservation status of everything – and we now have ways to achieve that with AI that are up to 90% accurate," says Dr Nic Lughadha. "The techniques are good enough to say, 'this area has a lot of species that haven't been assessed but are almost certainly threatened'. And knowing that will enable us to identify the most important areas to conserve in the immediate future."

This chapter is based on the following scientific paper published in *Plants, People, Planet*, where you can find more information and references: Nic Lughadha et al. (2020). Extinction risk and threats to plants and fungi. *Plants, People, Planet* 2(5). DOI: https://doi.org/10.1002/ppp3.10146

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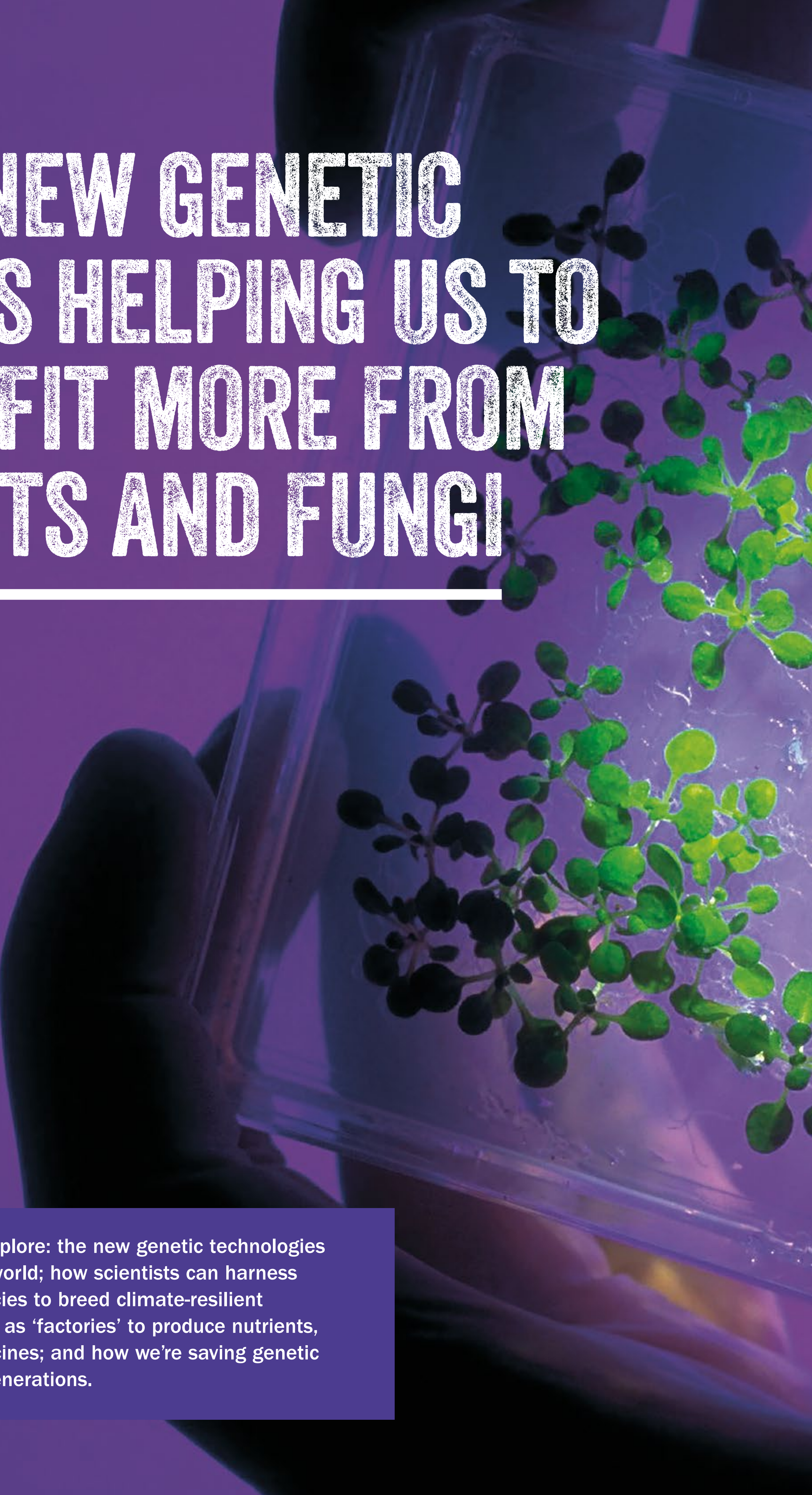
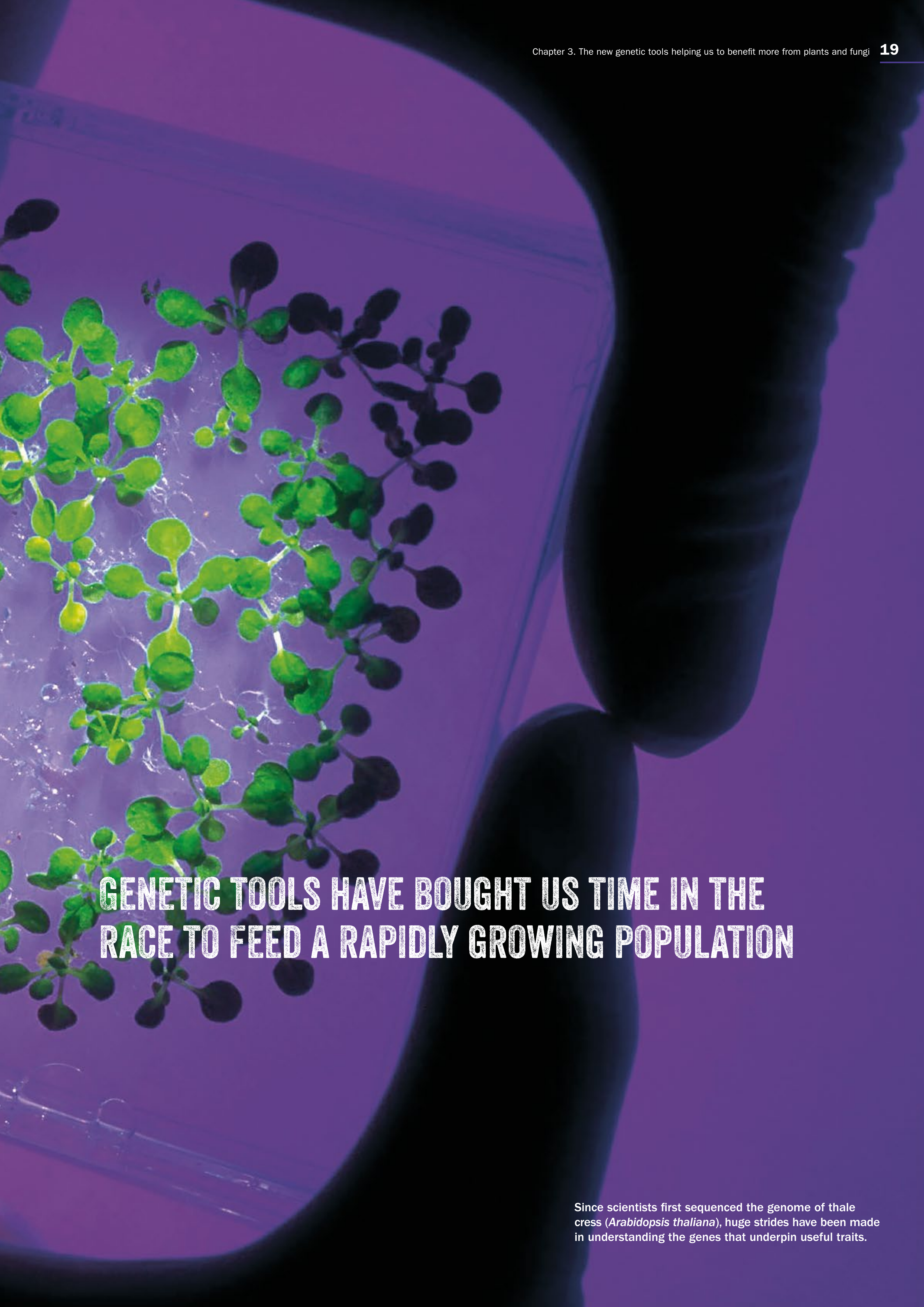
Explore Chapters 3–7 to learn about how we are unlocking the useful properties of plants and fungi.

THE NEW GENETIC TOOLS HELPING US TO BENEFIT MORE FROM PLANTS AND FUNGI



In this chapter, we explore: the new genetic technologies helping us feed the world; how scientists can harness genes from wild species to breed climate-resilient crops; the fungi used as ‘factories’ to produce nutrients, chemicals and medicines; and how we’re saving genetic diversity for future generations.



GENETIC TOOLS HAVE BOUGHT US TIME IN THE RACE TO FEED A RAPIDLY GROWING POPULATION

Since scientists first sequenced the genome of thale cress (*Arabidopsis thaliana*), huge strides have been made in understanding the genes that underpin useful traits.

NEW GENETIC TOOLS AND APPROACHES ARE INCREASING THE PRECISION WITH WHICH CROPS CAN BE BRED AND PINPOINTING NEW APPLICATIONS FOR FUNGI. THEIR USE WILL BE CRITICAL TO FEEDING THE PLANET'S RISING POPULATION AND REDUCING AGRICULTURE'S DAMAGING IMPACT ON THE NATURAL ENVIRONMENT.

By 2050, there will be two billion more people on the planet than there are now. As cities swell to accommodate them and climate change affects weather patterns, the amount of land and water available to grow crops and raise livestock will shrink. So, we will have to feed more people and develop new renewable bioproducts, while reducing pressure on and revitalising the degraded ecosystems that are our planetary life-support system. The question is, how?

One way is to employ genetic tools and techniques developed in recent years to make plants and fungi more useful to us. For example, we can breed genetic diversity that exists in wild species back into modern food, fuel and other crops. This will make them more robust, so they are able to tolerate shifting climatic conditions and fight off emerging pests and diseases. And we can apply new molecular approaches to understanding and re-engineering fungal processes, for medicine and food production.

THE RISE OF PLANT AND FUNGAL BREEDING

Many modern crops have low genetic diversity. This is the result of continuous selection and breeding that has taken place over thousands of years. Early farmers would have chosen to breed from plants that had a high yield, bore tasty fruit or coped well with the prevailing environmental conditions. We know they also selected for traits that made crops easier to harvest, by, for example, rejecting plants that readily shed seeds. With no knowledge of genetics, they would have made their choices based on visual characteristics. However, limiting the plants they bred from would have gradually eroded the genetic diversity in their crops.

The field of genetics only emerged in the 19th century, after Augustinian monk Gregor Mendel unravelled the laws of inheritance through studying pea plants. Further developments for plants came in the late 19th and early 20th centuries, when hybridisation experiments in Europe yielded a new oat variety and wheat hybrids with enhanced yields. And a great stride was made in 1953 when molecular biologists discovered the structure of DNA. The first fungal genome (the complete set of genetic information, including all genes) to be sequenced was baker's yeast (*Saccharomyces cerevisiae*) in 1996, with the first plant genome, that of the thale cress (*Arabidopsis thaliana*), sequenced four years later. Two decades on, the genomes of more than 3,000 fungal and 500 plant species have been sequenced, and these numbers are growing rapidly as sequencing speed increases and costs fall. This new field of science has enabled scientists to match particular traits observed in plants to their underlying genetic make-up, a capability of great value in crop breeding. Plant breeders search populations of wild or lightly domesticated species for different forms of genes (known as alleles) and try to combine them favourably to make crops with desirable properties. "Many organisms, including humans, contain two copies of each gene within each cell, and children inherit one copy from each parent," explains Dr Paul Kersey, Deputy Director of Science at Kew. "By ensuring your parent plants each have two identical copies of a desirable allele, then you can guarantee the offspring will show the favoured trait."

In theory, the ideal end result would be a perfectly engineered crop line, where every position in the genome would have identical copies of the most favourable alleles. However, sometimes an allele for an undesirable trait will play an important role in the biology of an organism (which is why highly bred dogs often end up with functional problems). And if the entire population only possesses one type of allele for a gene, even one that offers a big advantage in a particular environment, plants can end up being over-engineered for the conditions they have been bred to thrive in. In the process of removing unwanted alleles, traits such as tolerance to different climatic conditions, or the ability to fight pests, can sometimes be lost.

Another challenge is that traditional crop breeding takes time. A breeder wanting to make an existing variety resistant to a particular disease must cross non-resistant and resistant plants, grow the offspring to maturity, infect them with the pathogen and test the response. They must repeat this process until they achieve a plant that combines the favoured traits of the original variety with disease resistance. Introducing a new rice variety into the field generally requires six to eight generations of inbreeding and takes around ten years.

Accelerating this process is critical, given the speed at which we must step up global food production. Fortunately, innovative approaches that exploit low-cost techniques for DNA sequencing, new molecular modification tools and advances in imaging technology are increasing the precision with which new plant and fungal varieties can be developed, as well as reducing the time required to get them to market.

NEW TOOLS FOR PLANT BREEDERS

By mapping the distribution of variant alleles across many plant genomes, it is possible to identify 'genetic markers': alleles whose presence is associated with desirable traits. Breeders can take the progeny from a cross and sequence them while young to see if they exhibit the required marker. As the individuals displaying this signature are likely to have the desired trait, growing plants to maturity and testing them, say, for disease resistance, is no longer required.

Another emerging option for accelerating breeding cycles is a technique called 'high-throughput phenotyping'.

New genetic techniques are reducing the time taken to bring new crops to market.

Traditionally, a highly experienced breeder might identify plants with certain traits, such as high yield, using eyesight alone. Modern imaging and drone technology are now enabling this process to be automated. Algorithms taught to recognise the visual signatures of desired traits are being used to analyse footage of plants imaged in automated greenhouses or captured by drones.

Genetic modification (GM) can bypass the need for a lengthy breeding process altogether. A desired transgene (a gene sourced from another species) or cisgene (one sourced from a member of the same species or a close relative) can be introduced directly into the genome of a cultivar that already possesses other desirable traits. In recent years, these techniques have been used to enhance the nutritional content of several crops, including increasing the iron and zinc content of rice, and boosting the omega-3 content of oilseed rape.

In perhaps the most famous example, ‘golden rice’ has been engineered using genes from the daffodil (*Narcissus pseudonarcissus*) and the soil bacterium *Erwinia uredovora* to produce betacarotene, a precursor of vitamin A. The hope is that this genetic form of fortification might help to reduce vitamin A deficiency. The deficiency causes between 250,000 and 500,000 children to go blind each year, and half die within 12 months of losing their sight.

Despite its clear benefits, GM has received bad press over the years because of the belief that it may harm the environment. Recent studies suggest that any ecological impact is likely to be influenced by the biology of the crop and of wild species growing nearby, as well as by the transgene incorporated into the plants. While it makes sense that we carefully regulate how GM is used, it is important that the possible environmental risks of cultivating GM crops are weighed against those of hunger, poverty and biodiversity loss due to the cultivation of less productive traditional crops.

Gene editing provides an alternative to inserting whole genes into crops. Currently, the most efficient, flexible and cheapest approach – known as CRISPR/Cas – is adapted from a genome-editing system that occurs naturally in bacteria. It enables DNA to be added, deleted or altered. This method has been used in food and other crops to improve yield, nutritional composition, digestibility, shelf life, tolerance to cold and drought, and resistance to disease, insects and herbicides. Only very small amounts of DNA are altered or introduced (sometimes only one single unit of the genetic code) and the change is precisely targeted.

“THERE IS A WEALTH OF DIVERSE METABOLITES TO EXPLORE USING GENOMICS, AND WE ARE ONLY AT THE BEGINNING OF THIS EXPLORATION”

Maize is one of the most widely grown crops but much diversity remains available to breeders.

ENHANCING FUNGI'S USEFULNESS

Despite being used in foods, drinks and medicines for at least 6,000 years, the enhancement of fungal species for humans has lagged behind that of plants. Targeted breeding of fungi for food only took off in the 1980s, when one of the first hybrid strains of the widely cultivated edible mushroom *Agaricus bisporus* was developed. Since then, scientists have produced many fungal hybrids, including those that are being tested for their ability to make new forms of beer and biofuels.

"Breeding fungi is very different from breeding plants because the sexual reproduction system in fungi can be much more complicated," says Dr Ilia Leitch, Assistant Head of Comparative Plant and Fungal Biology, and Senior Research Leader at Kew. "With plants, you can often simply take two individuals and cross them. But with fungi, there can be a whole complexity of mating types; this makes breeding fungi to have new characteristics much more challenging."

Fungi are also fundamental to the methods used to synthesise important products that we rely on in our everyday lives. These range from medicines, such as statins and antibiotics, to biofuels. Some have diverse uses; for example, species of *Penicillium* are used to produce antibiotics, contraceptives and cheese.

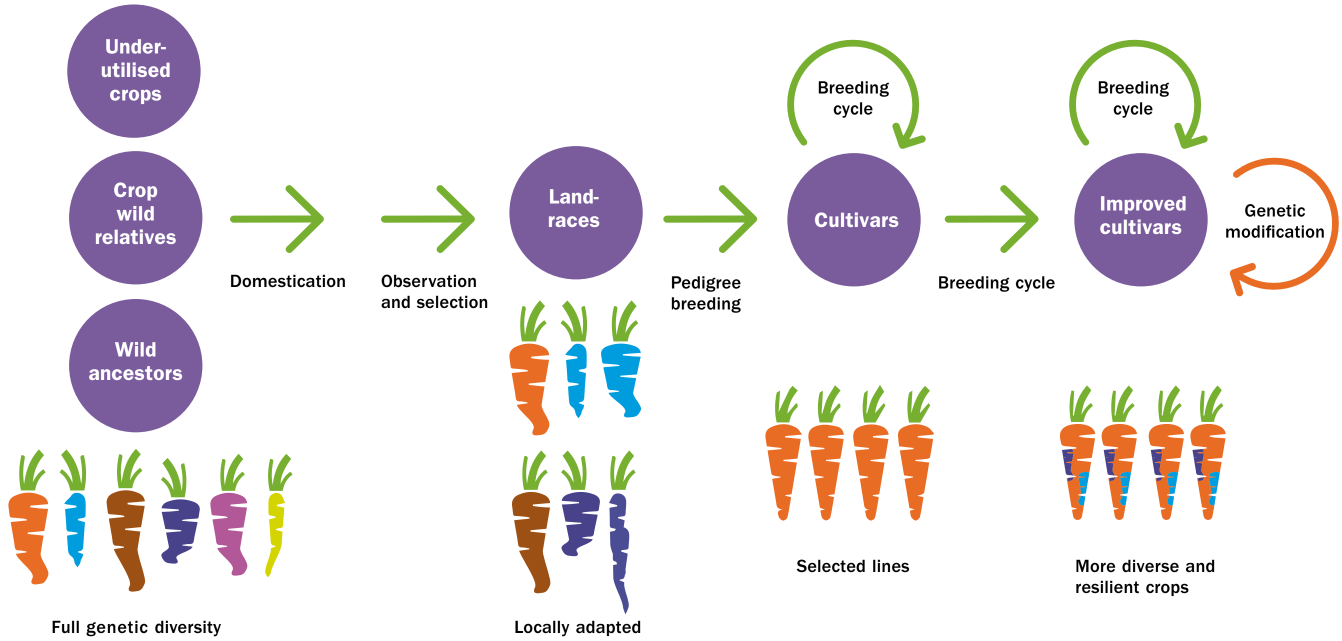
"There are natural uses of fungi, where you exploit natural products such as proteins or antibiotics for human purposes," explains Dr Kersey. "And then there are uses where you use the fungal cell as a 'factory', subverting the fungal metabolism to make a particular product. It is desirable to use fungi in this way, as they are quick to grow in liquid culture at a relatively high density. Chemical engineering companies grow fungi to produce industrial quantities of nutrients, chemicals, medicines and so on."

In the past 15 years, the sequencing of fungal genomes has improved our understanding of the workings of fungal secondary metabolites, compounds associated with many useful biological activities. These developments, together with advances in computational methods and tools for understanding genomic data, have greatly increased our ability to identify and produce fungal bioactive compounds and helped scientists find new ways to screen for them. "The analysis of fungal genomes has shown us that fungi can produce many more bioactive compounds than we currently know," says Dr Jérôme Collemare, of Westerdijk Fungal Biodiversity Institute, in Utrecht, the Netherlands, who contributed to the review on which this chapter is based. "There is a wealth of diverse metabolites to explore using genomics, and we are only at the beginning of this exploration."

A promising find is that bacteria–fungi and fungi–fungi co-cultivation often give rise to new compounds with important antimicrobial properties. For example, scientists were able to prompt the fungus *Coprinopsis cinerea* to produce the antibacterial compound 'Lagopodin B' (a potential new antibiotic) by cultivating it in the presence of bacteria. However, so far, only interactions specific to particular combinations of species have been discovered, so further exploration is needed to unlock the full potential of this approach.

FIGURE 1: The development of modern crops

Early farmers selectively bred from plants with favoured traits, which gave rise to landraces suited to local conditions. Later, commercial breeding of cultivars resulted in uniform crops with little genetic diversity. Today, breeders seek crop wild relatives and landraces with useful properties, such as drought resistance, so they can harness their genes to make modern crops more resilient.



RECLAIMING GENETIC DIVERSITY

To overcome the loss of genes arising from plant and fungal breeding programmes, scientists have begun searching for additional sources of genetic diversity. For plants, there are two promising sources: crop wild relatives (CWR), the wild species from which modern crops derive and their close relatives; and landraces, which are genetically diverse varieties of the same species as the elite lines of today's crops (see Figure 1). Landraces have been produced by farmers employing traditional agricultural practices, rather than modern breeding programmes, by saving seeds from plants with traits that enable them to thrive in their local environments.

To retain genetic diversity for use in future breeding programmes, we must conserve CWR and landraces. *In situ* conservation of CWR involves preserving the natural habitats where they grow, including whole ecosystems. In contrast, saving the genetic diversity held within landraces is achieved through their ongoing cultivation by farmers. *Ex situ* conservation is where genetic material from plants is conserved outside natural habitats, for example in seed banks.

Initiatives such as the 'Adapting Agriculture to Climate Change' programme, led by the Crop Trust in partnership with Kew and others, have helped to plug gaps in *ex situ* CWR collections and ensure genetic material is curated and stored in seed banks so as to safeguard its long-term viability. However, since scientists estimate that 8–20% of flowering plant species cannot be stored this way because their seeds do not tolerate drying, alternative storage approaches, such as cryopreservation (rapid freezing and storage at very low temperatures) and pollen storage, are being developed.

FUTURE USES FOR GENETIC TECHNOLOGY

The challenge facing humanity of feeding more people with less land and water resources while nurturing the environment, is enormous. However, nature provides a much larger store cupboard of species than we currently use. For example, of the 7,039 edible plant species documented in Kew's dataset of useful plants (see Chapter 4), we rely on just 15 for the bulk of our food energy intake, and we have barely scratched the surface when it comes to utilising fungi. Applying our expanding knowledge of genetics to these natural resources to develop new foods, medicines and other products (see Chapters 4, 5 and 6) is our best hope of supporting both people and planet in the future.

This chapter is based on the following scientific paper published in *Plants, People, Planet*, where you can find more information and references: Kersey et al. (2020). Selecting for useful properties of plants and fungi: Novel approaches, opportunities and challenges. *Plants, People, Planet* 2(5). DOI: https://doi.org/10.1002/ppp3.10136

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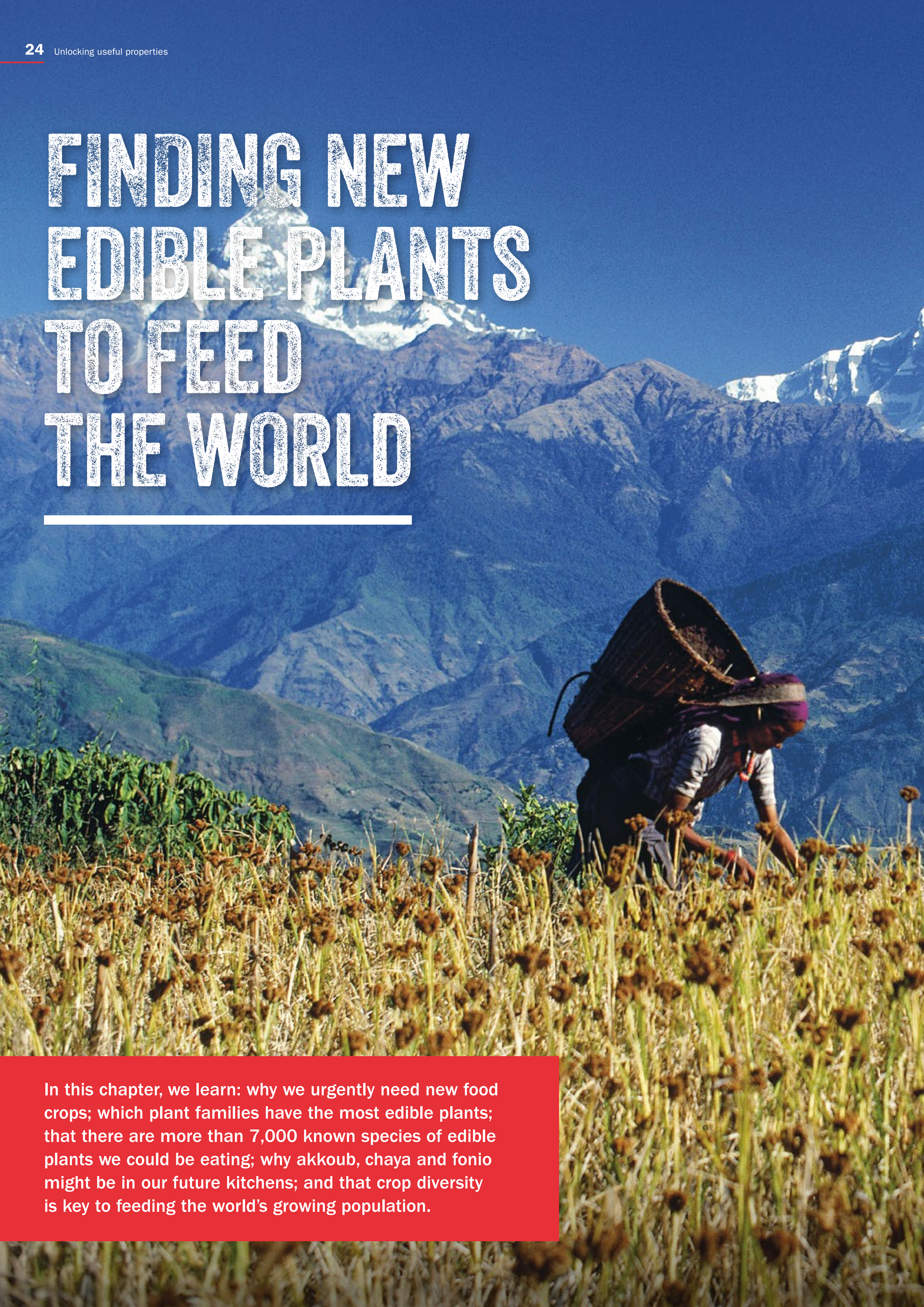
Read Chapter 4 to find out how making better use of underutilised species may also help to enhance future food security.

FINDING NEW EDIBLE PLANTS TO FEED THE WORLD



In this chapter, we learn: why we urgently need new food crops; which plant families have the most edible plants; that there are more than 7,000 known species of edible plants we could be eating; why akkoub, chaya and fonio might be in our future kitchens; and that crop diversity is key to feeding the world's growing population.

A farmer harvests millet in Nepal. Several varieties of millet remain overlooked by mainstream plant breeders but could be developed for wider use.

RELYING ON A HANDFUL OF CROPS TO FEED THE GLOBAL POPULATION HAS CONTRIBUTED TO MALNUTRITION AND LEFT US VULNERABLE TO CLIMATE CHANGE. KEW SCIENTISTS AND COLLABORATORS SUGGEST THAT OVERLOOKED AND UNDERUTILISED PLANTS HOLD THE KEY TO FUTURE-PROOFING FOOD PRODUCTION AROUND THE WORLD.

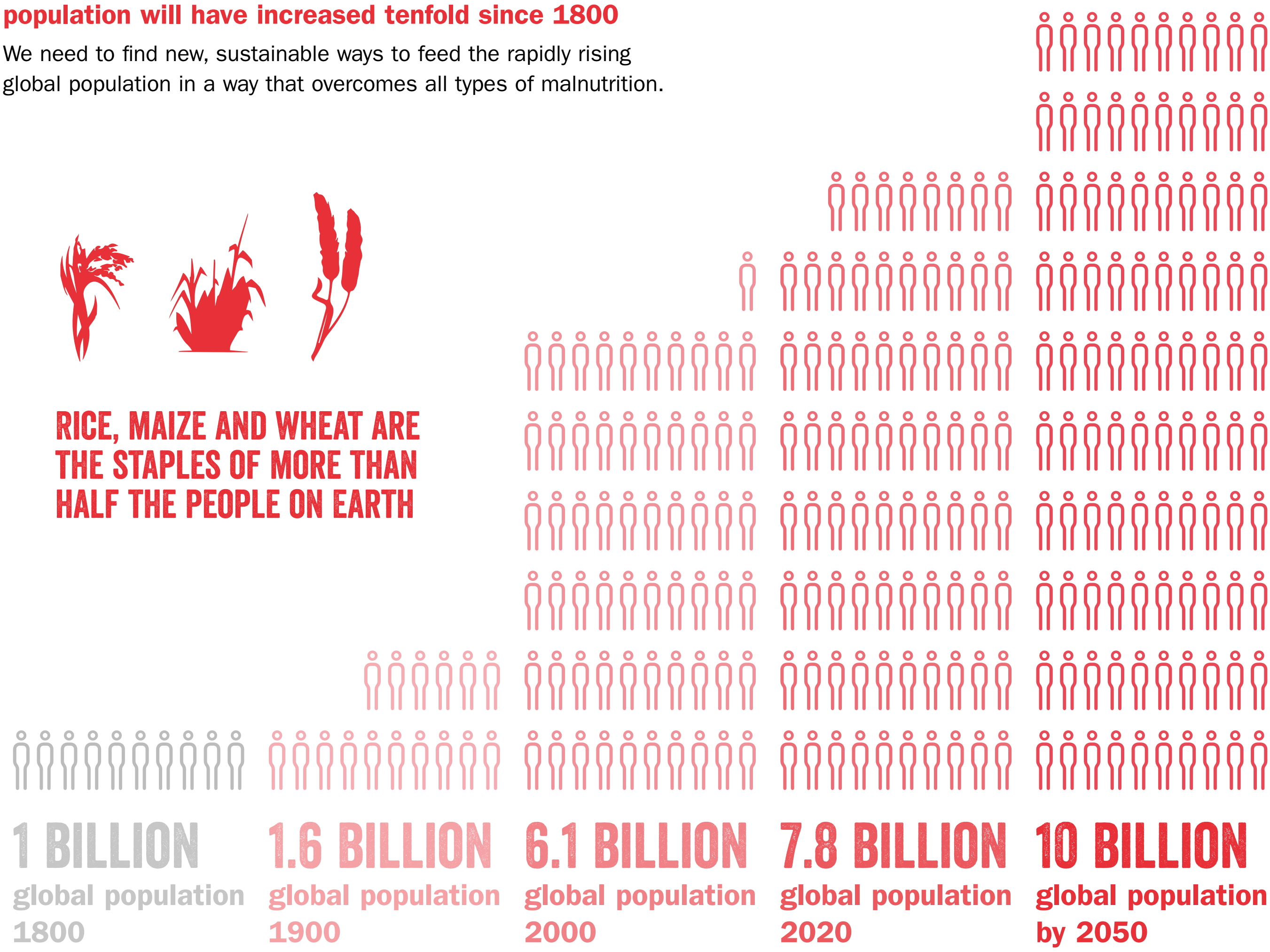
When it comes to feeding our future population, the world is in a precarious position. According to the Food and Agriculture Organization of the United Nations (FAO), just 15 crop plants contribute to 90% of humanity's energy intake, and more than four billion people rely on just rice, maize and wheat. Millions of people around the world suffer from hunger or obesity because they lack a balanced, nutritious diet, and this figure will likely rise as the global population expands to an estimated ten billion by 2050 (see Figure 1).

Meanwhile, climate change is threatening to unleash weather conditions, pests and diseases that our current crops will struggle to cope with. If humanity is to thrive in future, we need to make our food production systems more diverse, resilient and environmentally sustainable. One option for doing this is to identify future nutritious crops that are better equipped to deal with the less predictable weather conditions to come. However, to do so, we first need to know more about what edible plants exist, where they grow, and what environmental conditions they favour, tolerate or are vulnerable to. Working with a team of international collaborators, scientists at Kew set out to answer these questions and pinpoint overlooked and underutilised plants that might be suitable as future crops under a changing climate.

"The conservation and sustainable use of the widest diversity of crops and varieties is intrinsically linked to sustainable agriculture and food systems," says Dr Rémi Nono Womdim, Deputy Director of the Plant Production and Protection Division at the FAO, who contributed to the research. "We wanted to address these vital issues and highlight the importance of using a broader diversity of crops to ensure a resilient, sustainable and nutritionally rich agricultural future."

FIGURE 1: By 2050, it is anticipated that the global population will have increased tenfold since 1800

We need to find new, sustainable ways to feed the rapidly rising global population in a way that overcomes all types of malnutrition.



Researchers found the pea family (Fabaceae) to have the highest number of known edible species.

RESEARCHING EARTH'S EDIBLE PLANTS

The scientists began by examining plants listed as 'human food' within a dataset of useful plant species collated in recent years by researchers at Kew. This unearthed 7,039 known edible plant species across 2,319 genera from 288 families. "The dataset includes wild species from which our modern crops derive; 'minor' or 'orphan' crops that have been 'neglected' by agricultural researchers, plant breeders and policymakers alike; and a range of wild species that rural and indigenous communities collect fruits, seeds, leaves and other edible parts from," explains Dr Tiziana Ulian, Senior Research Leader in Kew's Natural Capital and Plant Health department. "The latter are often an important source of micronutrients, such as vitamins and minerals."

The next step was to find out more about the taxonomic diversity of these plants – in other words how widely they are spread across the 'tree of life'. The team found that the most important sources of human food were almost all vascular plants (flowering plants, conifers and other gymnosperms, ferns, horsetails and clubmosses), accounting for 7,014 species of the 7,039. The remainder were bryophytes (mosses, liverworts and hornworts), and green and red algae. The edible vascular plant species belonged to 2,300 genera from 272 families. The families yielding the highest number of edible plants were the pea family (Fabaceae; 625 edible species), palm family (Arecaceae; 325), grass family (Poaceae, which includes cereals; 314), mallow family (Malvaceae, which gives us cocoa, okra and durian; 257) and daisy family (Asteraceae, which includes sunflowers and lettuces; 251).

The researchers were keen to find out how the distribution of these edible species across plant families compared to that of currently used major food crops. Of the edible plants extracted from Kew's dataset, only 417 species (5.9%) featured on a list of major crops compiled by the FAO. Three of the richest families for contemporary crops also hosted species recorded as edible on the useful plant list – the pea family (51 species), grass family (27 species) and mallow family (21 species). This overlap suggests that potential exists for bringing to the wider market underutilised species that are presently only used locally as foods.

When the scientists mapped the global distribution of the edible plants, they found that the number of species decreased from low to high latitudes. This tallies with the pattern seen for total plant diversity. By comparison, the proportion of major crops tends to increase from species-rich, forested, warm and wet areas, to regions characterised by drier climates, rugged terrains and large human settlements. There are very few highly domesticated plants found at high latitudes, as with wild species. Understanding where both underutilised species and widely grown food crops thrive at the present time can help us identify what plants will grow best where under forecast future climatic conditions.

FIGURE 2: Foods of the future

These plant-based foods, already used locally around the world, could be coming to your fridge soon.

AKKOUB

Gundelia tournefortii **(Asteraceae)**

A thistle-like plant that grows almost exclusively on undisturbed rocky soils in the eastern Mediterranean and Middle East.

Food uses

The unripe inflorescences (flower heads) are consumed as a vegetable in many ways, including fried with olive oil and garlic; pickled; added to omelettes; or eaten with meat and chickpeas.

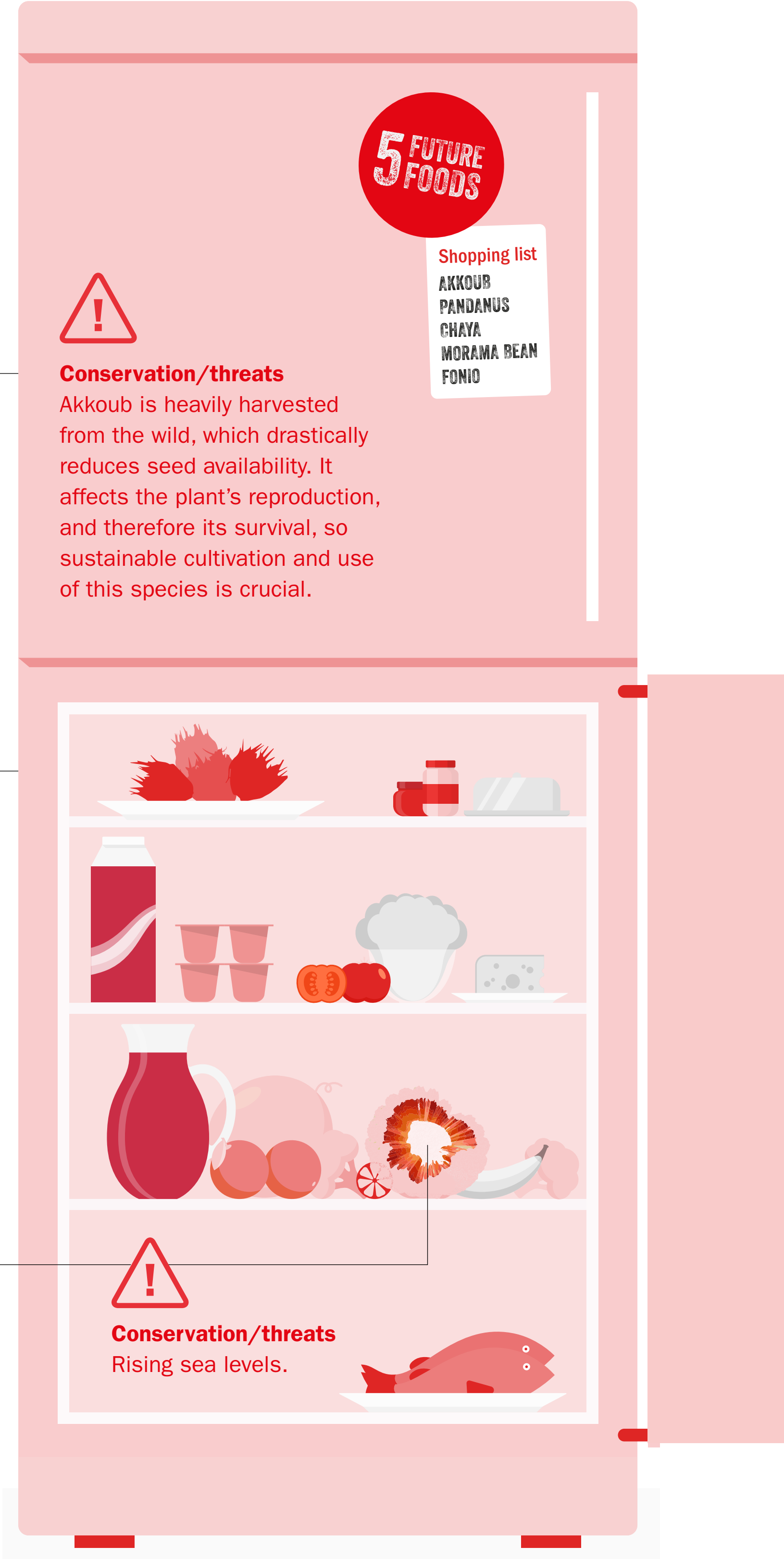
PANDANUS

Pandanus tectorius **(Pandanaceae)**

A small-trunked tree, also known as the screw pine, which grows in coastal lowlands from Hawaii to the Philippines. Supported by prop roots, it can withstand drought, strong winds and salt spray.

Food uses

Male and female pandanus grow as separate trees. The female plant produces large segmented fruit akin to a pineapple. This can be either eaten raw or cooked. The leaves are often used to flavour dishes.



CHAYA

***Cnidoscolus aconitifolius* (Euphorbiaceae)**

A large fast-growing leafy shrub native to the Yucatán Peninsula of southern Mexico.

Food uses

The highly nutritious leaves and shoots of chaya, also known as tree spinach, are a popular vegetable in Mexican cuisine. They are high in protein, vitamins, calcium and iron. However, raw chaya leaves are highly toxic and require simmering in water for 20 minutes.

MORAMA BEAN

***Tylosema esculentum* (Fabaceae)**

A drought-tolerant trailing perennial native to arid parts of southern Africa.

Food uses

Widely eaten, when roasted the seeds taste similar to cashew nuts. The beans are boiled with maize meal, or ground to a powder for making porridge or a cocoa-like drink. They also yield oil, butter and milk, and can be eaten as a meat substitute. The tuber and young stems are high in protein. Older tubers contain 90% water by weight.

FONIO

***Digitaria exilis* (Poaceae)**

A grass species that grows wild across the savannas of West Africa.

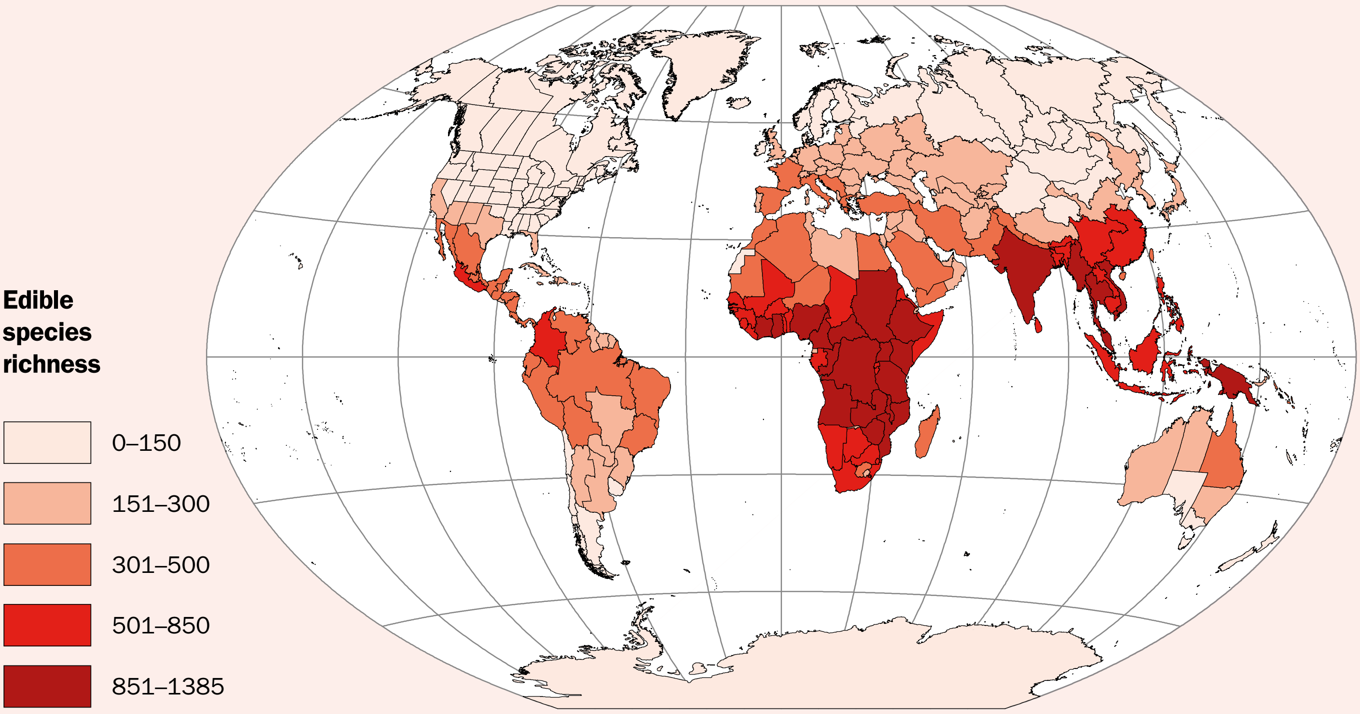
Food uses

Fonio is cultivated locally as a cereal crop. Fast growing, it can tolerate dry conditions but is labour-intensive to harvest. Its small grains are used to make thick and thin porridges, couscous and drinks. The cereal is high in iron, calcium and several essential amino acids.

THERE IS POTENTIAL TO BRING UNDERUTILISED SPECIES PRESENTLY ONLY USED LOCALLY AS FOODS TO THE WIDER MARKET

FIGURE 3: The global species richness, by country or state, of 6,959 of the 7,039 edible plant species identified by the review team

The darker shading highlights locations where there is high abundance of edible plant species.



FUTURE FOODS AT RISK

The International Union for the Conservation of Nature (IUCN) Red List of Threatened Species is the go-to indicator for the conservation status of the world's biodiversity. Of the 7,039 edible plant species in Kew's dataset, 30% appear on the 2020 IUCN Red List. Although most species (78%) are identified as 'Least Concern', more than 234 species (11%) are reported as being threatened with extinction. Without efforts to conserve them, we could lose potential foods before we have even understood their value.

Many food crop species are grown quite widely, so it is likely that their extinction risk will be relatively low. However, particular populations, including some significant farmers' landraces that are well adapted to grow under local climatic and environmental conditions, might still be threatened. An example listed online on the Brockwell Bake Wheat Gateway is the Welsh wheat landrace 'Hen Gymro', which disappeared from cultivation in the 1920s. Breeding programmes now aim to reintroduce it to south-west Wales, where its tendency to show resistance to rusts makes it ideally suited to the moist, mild climate. Landraces of less widely grown crops are also under threat. 'Edemert', a landrace of the banana relative enset (*Ensete ventricosum*) with distinct characteristics and uses, is known from only one community in Ethiopia. It is therefore vital that future conservation priorities reflect important local variations within species, as well as capturing the global picture.

PINPOINTING POTENTIAL CROPS

Informed by literature and knowledge from collaborative projects, networks and international agencies, the scientists outlined a selection of promising neglected and underutilised edible plant species (see Figure 2 for examples). Ranging from the peach palm (*Bactris gasipaes*) of the Americas to the bulbous chervil (*Chaerophyllum bulbosum*) of Europe and marula (*Sclerocarya birrea*) from Africa, they encompassed both wild species and crops that have been cultivated locally. Many of the species have multiple uses, rather than simply being food. For example, the shea tree (*Vitellaria paradoxa*) from Africa, which has nutritious edible fruits and flowers, yields a butter primarily used in cosmetics. Many African countries are rich in edible plant species (see Figure 3).

"One of my favourites is the baobab (*Adansonia digitata*)," says Dr Ulian. "This African 'upside down' tree is a multi-purpose species; you can use almost every part of the plant. The fruits and seeds are eaten by local people, the white pulp is used medicinally to treat fevers and diarrhoea and can be mixed with water to make a refreshing drink, and the bark fibre is used to make paper, rope, and clothing. On top of that, water is held in the trunk and the tree also provides shade. The fruits, in the form of powder, have already reached the London market. The powder can be sprinkled on cereal or yoghurt for breakfast or mixed into smoothies and juices, providing a rich source of vitamin C, fibre and antioxidants."

LESSONS FROM THE PAST

Successfully developing future foods will require us to learn from our previous mistakes. In the 1960s, when droughts in India threatened wide-scale starvation, scientists developed new wheat varieties. These made more efficient use of soil nutrients; had shorter, stiffer stems that could support the weight of heavier ears of grain; and could grow at any time of the year, enabling farmers to sow more crops annually. New irrigation schemes, pesticides and fertilisers helped to maximise food production. As a result of this ‘Green Revolution’, cereal outputs more than doubled in Asia between 1970 and 1995, significantly reducing the risk of hunger.

However, this boost came with an environmental cost. The shift in practices polluted waterways, degraded land, reduced biodiversity and made crops more susceptible to pests and diseases. Perhaps most importantly, the Green Revolution accelerated the cultivation of crops as monocultures. Selectively breeding crops for traits such as high yield and consistent plant height facilitated mechanised harvesting. Retaining genes that conferred these favoured traits resulted in other genes being lost, such as those that made plants better able to tolerate varied environmental conditions.

Ultimately, the Green Revolution produced crops that met the demands of large-scale cultivation but which had diminished genetic diversity – and therefore lower resilience (see also Chapter 3). And because subsidies, higher yields and other factors encouraged farmers to grow the new ‘designer’ crops, they stopped producing more genetically diverse and resilient local varieties. Many of those varieties, and the traditional knowledge associated with growing them, became lost as a result. This has ultimately affected dietary nutrition because the crops farmers abandoned had previously been important sources of critical micronutrients – such as iron, provitamin A and zinc – for poor communities.

A NEW ERA FOR FOOD PRODUCTION

To make our food systems more robust in future, we must diversify the spectrum of species used, protect biodiversity and safeguard essential ecosystem services that maintain good soil and water quality. It is a tall order, as the recent development of quinoa (*Chenopodium quinoa*) as a global crop shows. Although this underutilised species from Latin America is now available in many countries, only a small number out of the 120 or so varieties that exist can be bought outside its region of origin.

Farmers are cultivating the varieties for which there is the largest market. As a result, global demand is being met by a few varieties known as ‘quinoa real-types’. “While we want underutilised species like quinoa to become more widely cultivated, the focus must be on using local species and diversifying the range used, to sustain local agriculture as a means of supporting local livelihoods, and achieving local and global food security,” says Dr Ulian. “This is because those local species are better adapted to the local conditions. Also, having not undergone mainstream breeding, they have a higher genetic diversity than major food crops.”

Multipurpose neglected and underutilised species from different regions, such as those identified by Kew and collaborators, will be key to shaping a more sustainable and diversity-driven agriculture in the future, while safeguarding ecosystems and the services they provide. However, if such foods are to compete in the existing marketplace (which is dominated by a few commodity crops), agricultural subsidies and incentives will need to be rethought. Whereas Green Revolution approaches were generally ‘top down’, with governments imposing particular crops on farmers, new approaches must be ‘bottom up’, where farmers help to co-design and co-deliver food production systems.

“The thousands of underutilised and neglected plant species, known also as orphan crops, are the lifeline to millions of people on Earth tormented by unprecedented climate change, pervasive food and nutrition insecurity and economic disempowerment,” says Dr Stefano Padulosi, Senior Scientist, Integrated Conservation Methodologies and Use, at the Alliance of Bioversity International and the International Center for Tropical Agriculture, who contributed to the study. “Harnessing this basket of untapped resources for making food and production systems more diverse and resilient to change, should be our moral duty to current and future generations.”

This chapter is based on the following scientific paper published in *Plants, People, Planet*, where you can find more information and references: Ulian et al. (2020). Unlocking plant resources to support food security and promote sustainable agriculture. *Plants, People, Planet* 2(5). DOI: https://doi.org/10.1002/ppp3.10145

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Read Chapter 5 to find out more about how plants and fungi could also help to diversify the crops used as renewable sources of energy.

TO MAKE OUR FOOD SYSTEMS MORE ROBUST IN FUTURE, WE MUST DIVERSIFY THE SPECTRUM OF SPECIES USED, PROTECT BIODIVERSITY AND SAFEGUARD ESSENTIAL ECOSYSTEM SERVICES

THE SEARCH FOR NEW PLANTS AND FUNGI FOR ENERGY

In this chapter, we investigate: why we only use six species for energy crops; the methods of producing 'green' energy that are harming the environment; India's success with community-scale energy initiatives; the problem plants being put to use to produce electricity; and why fungi are key to future sustainable energy production.

6 CROP SPECIES YIELD 80% OF GLOBAL INDUSTRIAL BIOFUEL

Problem plants, such as the river-choking water hyacinth (*Pontederia crassipes*), are among species being explored as new sources of bioenergy.

ENABLING EVERYONE TO ACCESS CLEAN, SUSTAINABLE ENERGY CALLS FOR LOCALLY BENEFICIAL ENERGY SYSTEMS BASED ON DIVERSE PLANT AND FUNGAL FEEDSTOCKS. RESEARCHERS, GOVERNMENTS AND INDUSTRY ALL HAVE A ROLE TO PLAY IN MAKING THIS HAPPEN.

Most of us take energy for granted as we tap away on our phones, switch on the lights, cook our meals and turn up the heating or air conditioning. But some 840 million people, mostly living in sub-Saharan Africa, Asia and Oceania, still have no access to electricity. And three billion people lack non-polluting cooking fuels and technologies.

Over the past 20 years, the energy sector has diversified from hydrocarbons into bioenergy, wind and solar, as part of efforts to cut carbon emissions and slow climate change. The continued need to rethink energy systems presents the opportunity to address energy poverty where it persists, and ultimately extend access to clean, sustainable energy to all. As renewable sources of bioenergy, plants and fungi have a huge contribution to make to reducing both carbon emissions and energy poverty. Fungi, in particular, have much unexplored potential within the bioenergy sector.

NATURE'S CONTRIBUTION TO ENERGY

A comprehensive evaluation of the plant and fungal kingdoms as sources of energy had been lacking, so an international team of researchers led by Kew set out to fill this knowledge gap. Their work involved assessing how plants and fungi currently contribute to energy security, and identifying species with the potential to be matched with emerging technologies and used at local scales in the future. They found that, despite the greatest need for biofuels and the richest biodiversity being in low-income countries (see Figure 1), most research has focused on growing a handful of plants in temperate settings.

"Research in bioenergy has focused almost exclusively on a very small number of plants that are grown as monocultures, posing further risks to deforestation and land-use conversion, and potentially resulting in food-versus-fuel conflicts as well," explains Dr Olwen Grace, Senior Research Leader in the Comparative Plant and Fungal Biology department at Kew. "Some potential plant and fungal sources of energy, which are in use on a small scale but could potentially be expanded, have been overlooked. Instead, research has focused on a few crop species grown for industrial energy supply chains."

NEW BIOENERGY CROPS NEEDED

Rather than helping to reduce greenhouse gases and alleviate energy poverty, some of the methods we currently use to produce bioenergy are harming the environment and people. Crop production, for example, is one of several causes of deforestation in the Amazon, releasing carbon dioxide (CO_2) to the atmosphere and threatening species. Sugarcane for bioenergy is one such crop.

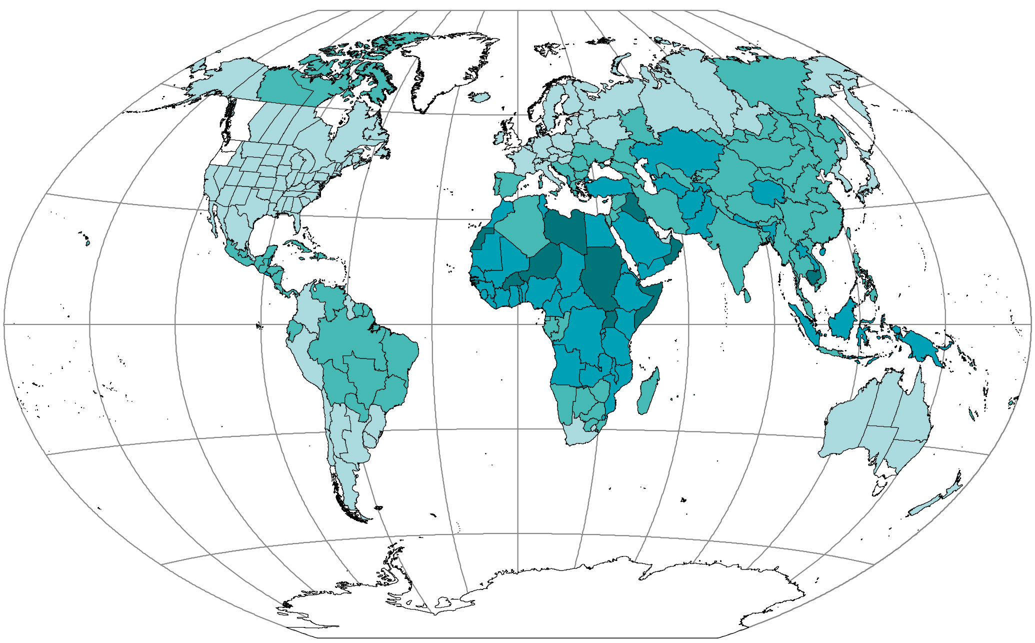
FIGURE 1: Regional variation in native fuel species (by country or state) as a proportion of total species richness

Countries with seemingly high proportions of fuel species, such as many African countries, are often among those suffering the most from energy poverty.

Proportion of native fuel species

Low

High



In 2019, a ban on sugarcane cultivation in the Amazon was lifted, which is likely to amplify rates of deforestation. And models predict that sugarcane will push agriculture into naturally vegetated areas of both the Amazon and South America's Cerrado savanna as a result of higher global demand for ethanol by 2030.

The use of traditional wood fuels for cooking, meanwhile, accounts for 1.9–2.3% of global CO_2 emissions. In some countries, such as Nepal and Uganda, unsustainable harvesting of wood for fuels supports 82–90% of energy used; despite this, both countries suffer from energy poverty. Smoke from open fires and inefficient cooking stoves, known as the 'killer in the kitchen', causes significant health problems, particularly for women and children.

Unsustainable harvesting of wood is even more prevalent in drylands, where water scarcity limits the number of trees. Accounting for around 41% of land globally, drylands overlap with regions affected by energy poverty. For example, in dryland areas of eastern Uganda, 98.8% of households use fuelwood for cooking and preserving food, mostly from *Acacia* species (trees and shrubs in the pea family, Fabaceae).

Further issues are arising from introductions of biofuel crops. For example, attempts to introduce *Jatropha curcas* (which is of Central and South American origin) to Africa and Asia for its seed oil have met with limited success. People have found collecting the fruits strenuous and time-consuming, handling the seeds has caused skin irritation, and appropriate processing technologies have not been widely available.

Jatropha curcas can thrive outside its native range, and future climate scenarios are set to give it a further boost. It is therefore possible it could spread uncontrollably in future, with implications for the species it interacts with. In Madagascar and Ethiopia, Australian *Grevillea* species introduced as fuel but rejected by locals have grown into unplanned, low-diversity forests.

LEADING THE WAY

Bioenergy initiatives that are having positive impacts on biodiversity and communities stand as examples for future initiatives. In East Africa, the indigenous tree species *Croton megalocarpus* supports a sustainable seed oil industry that provides biofuel for electricity. One microenterprise, EcoFuels Kenya, sources more than 3,000 tonnes of wild-collected nuts each year. The company processes the nuts to extract oil which replaces diesel in generator engines, while the husks are converted to livestock feed and organic fertiliser.

"It's a brilliant example of local-scale fuel production," says Dr Grace. "Not only is it a sustainable industry supplying businesses but it has the potential to be used for household energy, and already benefits thousands of people, many of them women, in rural Kenya."

Use of firewood for cooking causes health issues and depletes habitats.

In southern India, Hassan Biofuels Park has pioneered the concept of community energy gardens. Sustainable local plant materials that are readily available to communities are matched with appropriate local bioenergy technologies. The approach encompasses cultivating these fuel plants on marginal and degraded land, and as shade trees; using household waste to supply additional biomass; engaging communities to manage wild forests sustainably; and initiatives to clear problematic introduced species.

Since this concept was launched in 2007, there have been significant changes in national and state biofuel policy and legislation in India in response, and the approach has now also been adopted in Nepal. "Globally a huge energy transition is taking place," says Prof. Jon Lovett, Chair of Global Challenges at the University of Leeds, UK, who was part of the Kew-led research team. "Technology such as bioenergy gasifiers, solar power and smart mini-grids are now available at a price that can enable a shift away from reliance on expensive large-scale energy infrastructure towards community-based systems, with energy generation and transmission developed in tandem with local needs."

New bioenergy solutions could bring considerable gains beyond the benefits of reduced energy poverty to biodiverse nations. The grass genus *Miscanthus* is among the first crops for which bilateral agreements have been developed under the Convention on Biological Diversity to guide breeding of new varieties from wild germplasm collections from Asia. A naturally occurring hybrid, *Miscanthus* × *longiberbis* has now been commercially grown to overcome the risks associated with cultivating introduced *Miscanthus* species as energy crops. The grass has also been proposed as a substitute crop to grow on land currently supporting maize for fuel, potentially using half the land and a third of the water to produce the same amount of bioethanol.

AN UNTAPPED RESOURCE

There are around 350,000 known species of vascular plants, of which at least 2,500 species are documented sources of fuel or bioenergy. Despite this, just six crop species – maize, sugarcane, soybean, palm oil, rapeseed and wheat – yield 80% of global industrial biofuel. These staple bioenergy plants are also important food crops, and conflicts have arisen over whether land should be used to grow food or fuel.

A better approach is to find new bioenergy crops that can be grown on marginal lands not needed for growing food, particularly in the world's drylands. Introductions of *Jatropha curcas* were motivated, at least in part, by its ability to thrive in such areas. However, the subsequent negative outcomes for biodiversity serve as a reminder that using local species is preferable.

"Bioenergy is an untapped resource in low-income countries that could help alleviate poverty, enhance community livelihoods and improve energy access in remote areas," says Dr Elisabeth Rianawati, Senior Researcher at the Resilience Development Initiative in Indonesia, who also contributed to the research.

Identifying promising new species to match with emerging technologies for small-scale bioenergy production calls for specialist knowledge of plant and fungal taxonomy. It is possible to use an understanding of the evolutionary relationships between plant species to identify relatives of already exploited species that might have similar useful properties. This approach is most effective when seeking species that share characteristics with a plant already in use (for example, one containing carbohydrates already used for bioenergy).

Another approach is to use automated methods to search across datasets to identify plants with particular characteristics. Widespread screening is needed to capture more data on traits of interest, such as oil, carbohydrate content, wood density, and habitat or cultivation preferences. With our knowledge of plants presently far greater than that of fungi, and therefore more identified material available for screening, these methods are presently more appropriate for identifying potential plant bioenergy sources. Only 148,000 species of fungi have been named to date, of an estimated 2.2–3.8 million. Fungi that might prove useful for bioenergy are therefore more likely to be discovered by broad, high-throughput genomic screening programmes.

Fungi have great potential within the bioenergy sector, for example expanding their current use for pre-treating woody plant material. Fungal enzymes produced by species such as the filamentous *Trichoderma reesei* break down vegetation and can be cultured sustainably. They can enhance bioenergy recovery from plants and also make more energy from waste products of bioenergy processes – waste glycerol from biodiesel production, for example. And microbial fuel cells can be run on fungal enzymes, such as those from baker's yeast (*Saccharomyces cerevisiae*), to generate electricity from plant biomass.

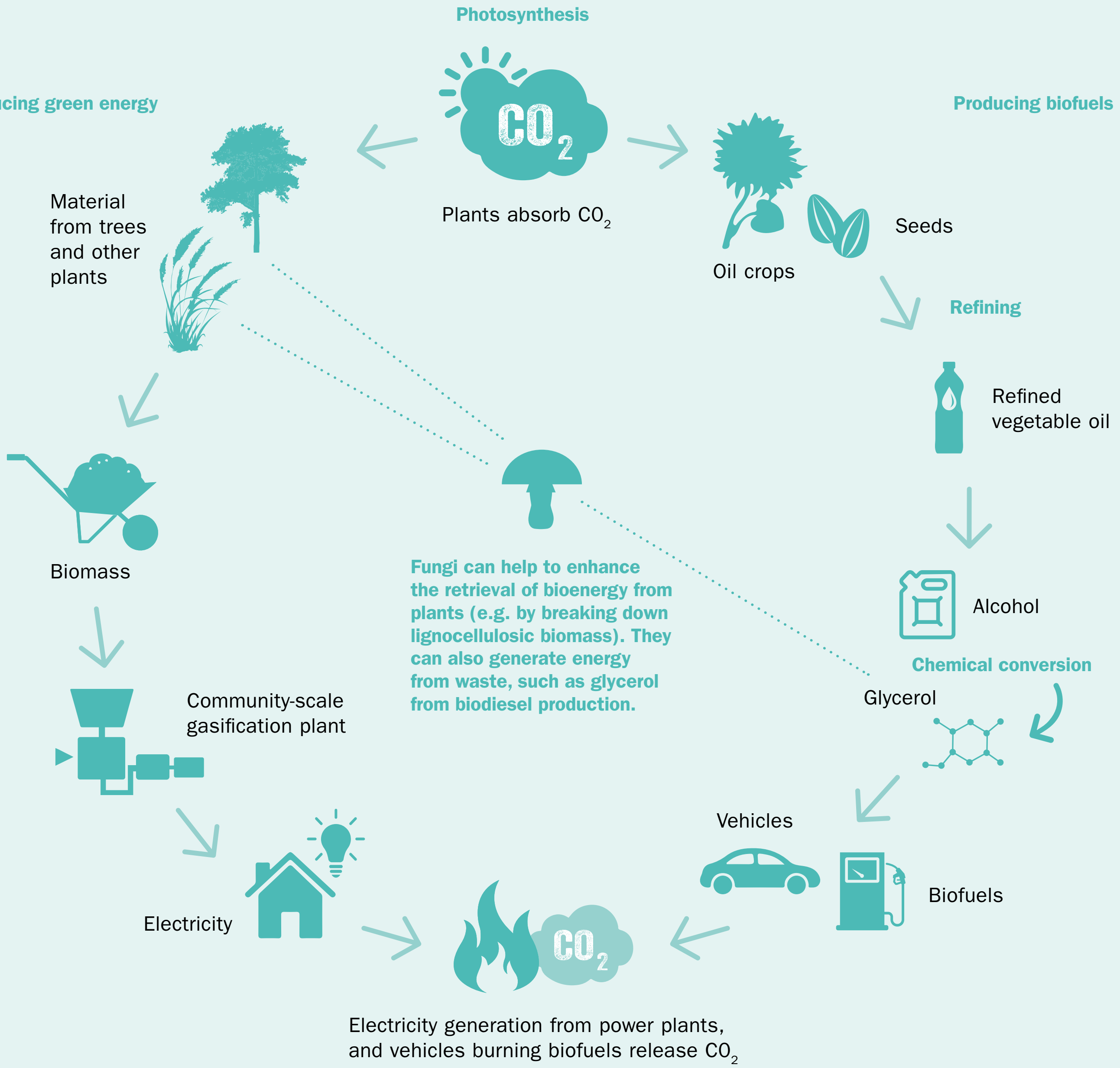
Problematic plant species are being turned into sources of bioenergy as a way to control them. For example, introduced aquatic plants that have spread rapidly are emerging as a new source of wet feedstocks in low-income countries. Plants such as water hyacinth that have caused problems by blocking waterways in the past, are now being processed to produce heat, electricity and bioethanol. Meanwhile, in arid environments, fast-growing succulent plant species that can thrive on marginal soils with limited irrigation are being investigated for bioenergy. Algae are another emerging source; they can be farmed offshore or in bioreactors, helping to minimise the impact of energy production on terrestrial biodiversity and land use.

RATHER THAN HELPING TO REDUCE GREENHOUSE GASES AND ALLEVIATE ENERGY POVERTY, SOME OF THE METHODS WE CURRENTLY USE TO PRODUCE BIOENERGY ARE HARMING THE ENVIRONMENT AND PEOPLE

A sugarcane plantation encroaches on rainforest in Brazil. Sugarcane is used to produce the biofuel ethanol.

BOX 1: Producing fuels and electricity from plants and fungi

A promising model for the future is for communities to produce renewable energy to meet their needs using species of local origin matched to appropriate technologies.



How plants and fungi provide us with bioenergy

Plants capture energy from the sun and store it in their tissues. This material, ranging from leaves to woody branches, can be chemically complex, incorporating oils, sugars and other compounds. We can convert energy stored in biomass into more useful forms by thermal or biological means. This makes plants ideal sources of bioenergy.

Thermal conversion of biomass produces heat and electricity from combustion (burning in the presence of oxygen), pyrolysis (decomposition of matter heated in the absence of oxygen) and gasification (conversion of plant matter in the presence of steam to carbon monoxide, carbon dioxide and hydrogen). Biological conversion involves anaerobic digestion or fermentation. Anaerobic digestion produces biogas (a mix of methane and CO_2), while fermentation yields liquid fuels for vehicles.

Generally, thermal conversion technologies require feedstocks with low moisture and ash levels but high lignin content (such as wood, straw and other forestry products), while biological conversion calls for wet feedstocks that are rich in carbohydrates (such as animal feedstocks, non-woody crops and biodegradable matter from sewage farms).

Fungi are used extensively to enhance the retrieval of bioenergy from plants. Looking to the future, they represent an exciting potential source of new bioenergy technologies.


In future, fungi are likely to play a major role within bioenergy.

ENDING ENERGY POVERTY

The United Nations Sustainable Development Goal 7 aims to address the lack of access to electricity and energy for cooking and ensure affordable, reliable, sustainable and clean energy for all. An important benefit of locally generated energy is that it helps to light homes in the evenings, meaning homework can be completed after dark. This has a positive outcome for education and for development in low-income countries. Plants and fungi represent a vast, untapped source of feedstocks for existing bioenergy technologies, which can help to achieve this goal. However, overcoming the negative impacts of current bioenergy provision requires the bioenergy sector to diversify with sustainable, local sources of feedstocks matched to accessible technologies (see Box 1).

Achieving this will require specific efforts from a range of actors. Researchers and funding bodies must scale up efforts to identify locally appropriate plant species with biofuel potential in low-income countries, where plant diversity is high and energy poverty most acute. Governments and international aid programmes need to introduce clean cooking technologies and encourage agrodiversity alongside biodiversity conservation. And industry should invest in technologies developed for local species that can supply varied ecosystem services within bioenergy 'landscapes', encompassing foods, carbon storage, shade, water management, air quality, support for pollinators and biocultural value.

"I think that energy poverty and Sustainable Development Goal 7 can be addressed sustainably within a decade if there is the political will, given that we have a diverse pool of plants and fungi to explore and a vast array of suitable emerging technologies," says Dr Grace. "There is real potential to harness the advances in engineering to support diverse, sustainable and resilient landscapes supporting the most essential human needs – food, water and energy.

This chapter is based on the following scientific paper published in *Plants, People, Planet*, where you can find more information and references: Grace et al. (2020). Plant Power: Opportunities and challenges for meeting sustainable energy needs from the plant and fungal kingdoms. *Plants, People, Planet* 2(5). DOI: https://doi.org/10.1002/ppp3.10147

Read Chapter 6 to find out how new technologies are enabling us to improve our use of plants and fungi in medicines.

NEW WAYS TO USE NATURE SUSTAINABLY IN HEALTHCARE

723 PLANT SPECIES THAT ARE USED MEDICINALLY ARE THREATENED WITH EXTINCTION

In this chapter, we learn: that nature represents a largely untapped medicine cabinet of treatments; how our current use of species for healthcare is causing biodiversity loss; that a compound found in apples inspired a new class of drugs; why fungi are key to securing drug supplies in the future; and that industrial waste is being used to make pharmaceutical steroids.

Artemisinin from the plant *Artemisia annua* is used to treat malaria. Examining the plant 'tree of life' is helping scientists pinpoint new medicines.

ALTHOUGH PLANTS AND FUNGI HAVE LONG BEEN USED AS MEDICINES, THIS USE HAS CONTRIBUTED TO BIODIVERSITY LOSS. NEW ADVANCES IN SCIENCE AND TECHNOLOGY ARE HELPING US DERIVE MEDICINES FROM NATURE MORE SUSTAINABLY.

Plants and fungi have provided or inspired some of our most important drugs (see Box 1). We have nature to thank for cancer-fighting vincristine and etoposide, the painkillers morphine and aspirin, the heart condition drugs digoxin and warfarin, and a suite of antibiotics, among others. However, the search for new drugs is far from over, because non-communicable diseases, including cancer and heart disease, remain responsible for almost 70% of deaths globally, and communicable ones, such as malaria and tuberculosis, also affect billions of people. The risk of new infectious organisms emerging is ever present, too, as the COVID-19 pandemic has shown.

With around 4,000 species of plants and fungi being scientifically described for the first time every year, the world's wild ecosystems represent a medicine cabinet of many as-yet-unknown therapeutics. However, our present use of natural products for healthcare is contributing to biodiversity loss, so we need to find new approaches that support the conservation of plants and fungi. Emerging technologies, such as the use of 'fungal factories' to manufacture pharmaceutical compounds, might provide a solution.

TAPPING INTO NATURE'S ARMOURY

We use plants and fungi as medicines by harnessing the complex compounds they produce as strategies for their own survival. These include compounds to ward off pests, diseases and other attackers, and for overcoming environmental challenges, such as high levels of ultraviolet light from the sun. For example, the Pacific yew (*Taxus brevifolia*) and *Cephalotaxus* species, both in the yew family (Taxaceae) produce the toxic compounds paclitaxel and homoharringtonine, respectively. These have been developed for use in certain chemotherapy regimens, as they destroy cancer cells.

The use of compounds from nature in mainstream medicine is extensive. Of 185 small-molecule drugs approved for cancer between 1981 and 2019, 65% were derived from, or inspired by, natural products. In recent years, a compound found in apples (*Malus* species) and other plants was the inspiration for a new class of drugs – the 'flozins' – developed to control glucose levels in people with diabetes. For chronic obstructive pulmonary disease, new drugs have been developed that are based on the alkaloid compound atropine, which occurs in some members of the potato family (Solanaceae), such as *Brugmansia* species. And plants are emerging as potential sources of vaccine adjuvants; for example, a chemical made by the soap bark tree (*Quillaja saponaria*) is included in a shingles vaccine and is being developed for use in vaccines against malaria and tuberculosis.

"Scientific advances are enabling us to explore the untapped potential of the world's plants and fungi for their medicinal value, and to discover other roles they may have to improve health and well-being," says Dr Melanie-Jayne Howes, Research Leader in Kew's Natural Capital and Plant Health department. "These scientific developments not only benefit humanity directly, but they also demonstrate the value of plants and fungi, providing an additional incentive for conserving biodiversity."

Since the accidental discovery of penicillin from *Penicillium rubens* in 1928, fungi have yielded many valuable drugs. Among them are the some of the most commonly prescribed medications in the UK – the cholesterol-lowering statins. These are derived from various filamentous fungi, including *Aspergillus terreus* strains and *Penicillium citrinum*. And the fungus *Tolypocladium inflatum* is used to produce the immunosuppressant ciclosporin, which helped to revolutionise the success of organ transplants.

Complementing such pharmaceuticals are herbal medicines, functional foods (those that provide benefits over and above their nutritional value) and dietary supplements such as nutraceuticals (foods, or parts of them, that have health benefits). Growth in the use of these is booming, driven by a rise in the prevalence of certain chronic diseases and the search for therapies where conventional treatments are lacking.

Alzheimer's disease, the most common form of dementia, provides an example. Since 2002, every drug developed for this disease has failed in clinical trials, and those that show promise are often not available for widespread clinical use. Consequently, there is much interest in investigating the role of nutraceuticals and plants already in our diet that may improve cognitive functions. At Kew, scientific research is in progress with partners to find plants that may help to slow cognitive decline associated with ageing or dementia.

Historically, unconventional medicines, primarily herbal remedies, have played a central role in the health systems of low-income countries, where mainstream healthcare is often too costly for many. For millions living in rural areas, traditional healers are the main health providers and sources of medicines; worldwide, as many as four billion people rely on herbal medicines as their primary source of healthcare. In China, herbal medicines represent around 40% of all healthcare services.

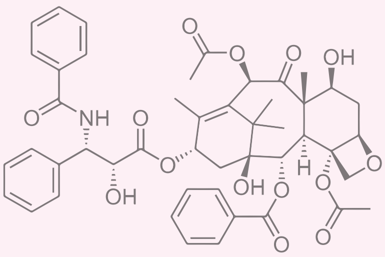
THE WORLD'S WILD ECOSYSTEMS REPRESENT A MEDICINE CABINET OF MANY AS-YET-UNKNOWN THERAPEUTICS

BOX 1: Plants and fungi we use as medicines

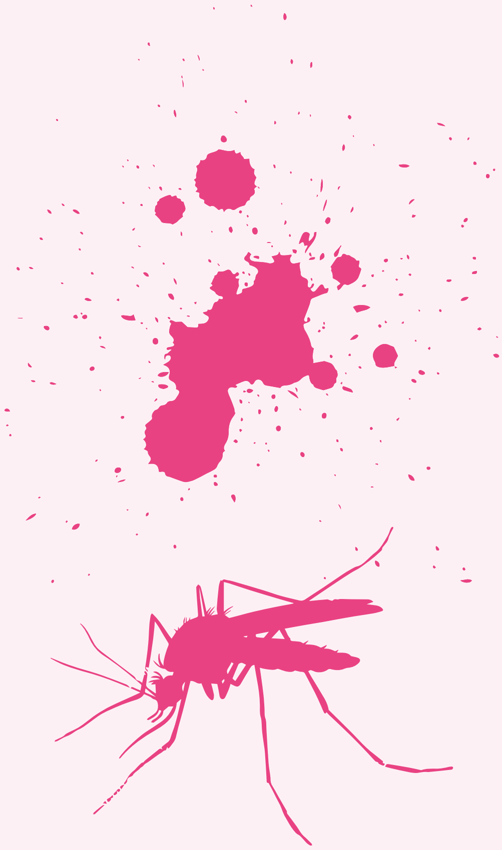
Scientists use various methods to seek out new treatments. These include examining traditional uses of species, exploring the similarities in related species where one is already used as a medicine, and using existing treatments for one disease to try to treat another.

CANCER

The Pacific yew (*Taxus brevifolia*) produces paclitaxel (below), a toxic compound that has been developed for use in some chemotherapy regimes.

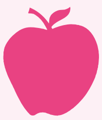


Two drugs used today in chemotherapy – vincristine and vinblastine – were developed from the Madagascar periwinkle (*Catharanthus roseus*).



MALARIA

Traditionally used as a tea to treat fevers in China, *Artemisia annua* is a source of artemisinin. This compound and its derivatives are used to treat malaria caused by the *Plasmodium falciparum* parasite.



DIABETES

In recent years, a compound found in apple (*Malus* species) and other plants was the inspiration for a new class of drugs – the ‘flozins’ – developed to control glucose levels in people with diabetes.

SHINGLES

The soap bark tree (*Quillaja saponaria*) contains chemicals called saponins. One, when purified, has been found to enhance the efficacy of certain vaccines. It is now used in a shingles vaccine.

DEMENTIA

Work at Kew has revealed that sage (*Salvia officinalis*), rosemary (*Salvia rosmarinus*) and lemon balm (*Melissa officinalis*) show promise against cognitive decline.

Natural Products

Of 185 small-molecule drugs approved for cancer between 1981 and 2019, 65% were derived from, or inspired by, natural products.

The global demand for naturally derived medicines, along with other pressures, is threatening some species. Of the 25,791 species of plants documented to be of medicinal use, 5,411 have been assessed under the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species. Of those, 723 (13%) are categorised as threatened. Only six species of medicinal fungi have been assessed, one of which, *Fomitopsis officinalis*, a wood-inhabiting parasitic fungus, has already been pushed to the brink of extinction.

South Africa is among the world's top users of medicinal plants, with some 27 million people relying on traditional healthcare. Overharvesting and the unsustainable use of wild medicinal plants is a major concern; experts believe that a drop observed in the number of species traded between 1998 (700) and 2013 (350) may be due to a reduction in available plant diversity. The collection of bulbs, bark and roots for sale is particularly destructive, leading to the plant dying after harvesting in around 86% of cases.

USING BIODIVERSITY MORE WISELY

Scientific and technological advances have the potential to help us make better use of plants and fungi as sources of medicines. The Plant and Fungal Trees of Life project, led by Kew, is helping to untangle the evolutionary relationships within each of these kingdoms based on their DNA. This could enable scientists to more accurately predict species most likely to produce similar compounds with medicinal properties.

By scrutinising the relationships revealed by these genetic trees of life, scientists can identify 'hot zones', where species with a particular medicinal use are clustered. For example, knowing that the bark of *Cinchona* (a genus of trees belonging to the coffee family, Rubiaceae) contains antimalarial quinine, has helped to identify the genus as a hot zone for other potential antimalarial compounds.

The subfamily Rauvolfioideae, part of the dogbane family (Apocynaceae), is another antimalarial hot zone. However, not all members of this subfamily have been reported to have antimalarial activity. An example is the genus *Skytanthus*, which originates from areas in South America where malaria is not present. Such plants might well contain antimalarial compounds, but local people are highly unlikely to have recorded them as useful against the disease if it is not transmitted there. Taking a phylogenetic approach therefore has the potential to reveal previously hidden knowledge about species that could yield medicinal compounds.

Since the 1990s, the pharmaceutical industry has shifted away from exploring new plant- or fungus-derived medicines. Necessary legislation to protect biodiversity, coupled with difficulties in isolating sufficient supplies of active chemicals from nature and a focus on synthetic drugs, have contributed to this. Now, the situation is changing. Libraries containing fractions of natural products are being made accessible to scientists, reducing the need for collection from the wild. And advances in analytical chemistry and computing are making it easier for scientists to identify the complex structures of potentially useful compounds from miniscule samples of plants and fungi.

"At Kew, we investigate the chemical diversity of plants and fungi to understand the scientific basis for their uses, including their role as sources of medicines, or for our health as part of our diet," explains Dr Howes. "To do this, we use analytical chemistry techniques to detect and characterise compounds, which often involves, as a first step, preparing an extract from sampled plant or fungal material. Emerging technologies mean we can now even detect and characterise compounds from preserved herbarium and fungarium specimens without damaging them, expanding access to a vast range of accurately identified species." (See also Chapter 8.)

Our expanding knowledge of the biosynthetic pathways that plants and fungi use to produce compounds is boosting our chances of creating sustainable supply chains for a wider range of medicines for the future. Once we know the specific genes and enzymes a species uses to synthesise a particular medicinal compound, we can potentially transport that biosynthetic pathway into a different organism, such as a yeast. The yeast is then able to produce that compound, once more reducing the need for researchers to collect material from the wild.

"Natural products can be very complex and difficult to synthesise," says Dr Jérôme Collemare, Group Leader at the Westerdijk Fungal Biodiversity Institute in Utrecht, the Netherlands, who contributed to the review on which this chapter is based. "The use of fungi is clearly an advantage because they can be used in fermentation-based industrial processes. Thanks to advances in genomics, synthetic biology and biotechnology, it is now possible to develop filamentous fungi as cell factories for the large-scale production of bioactive compounds, not only of fungal origin, but also from other organisms such as plants."

The Himalayan and American mayapples (*Podophyllum hexandrum* and *P. peltatum* respectively) contain podophyllotoxin, a compound used in the manufacture of some anti-cancer drugs. Containing a higher level of podophyllotoxin, *P. hexandrum* is the preferred source; however, its trade is restricted because wild populations are under threat. Scientists recently identified the genes responsible for biosynthesising podophyllotoxin, and reconstituted this metabolic pathway in a different plant, *Nicotiana benthamiana*. This breakthrough could make it possible to produce the compound more sustainably in future.

The role of plants and fungi for medicines is evolving beyond simply providing new compounds to treat diseases. Our growing understanding of natural product chemistry is enabling plant and fungal molecules to be discovered that

SCIENTIFIC AND TECHNOLOGICAL ADVANCES HAVE THE POTENTIAL TO HELP US MAKE BETTER USE OF PLANTS AND FUNGI AS SOURCES OF MEDICINE

The yew species *Taxus brevifolia* is the original source of the anti-cancer drug paclitaxel.

Strains of the filamentous fungus *Aspergillus terreus* are a source of statins, which are drugs used to lower cholesterol.

***Brugmansia sanguinea*, native to Latin America, is one source of the drug atropine. This species is now extinct in the wild.**

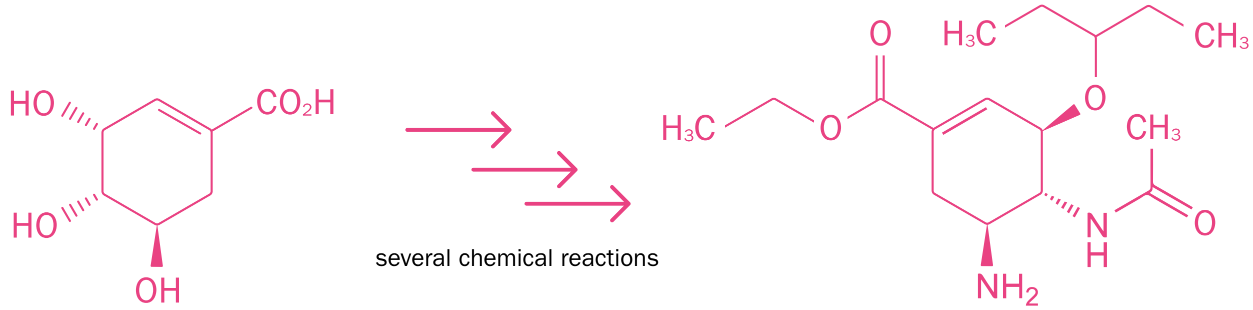
A compound that occurs in species from the apple genus (*Malus*) inspired drugs used to control glucose levels.

Only six species of medicinal fungi have been assessed for the IUCN Red List of Threatened Species. Eburiko (*Fomitopsis officinalis*), which is one of them, is in decline and already believed to be extinct in Spain.

OUR EXPANDING KNOWLEDGE OF THE BIOSYNTHETIC PATHWAYS THAT PLANTS AND FUNGI USE TO PRODUCE COMPOUNDS IS BOOSTING OUR CHANCES OF CREATING SUSTAINABLE SUPPLY CHAINS FOR A WIDER RANGE OF MEDICINES FOR THE FUTURE

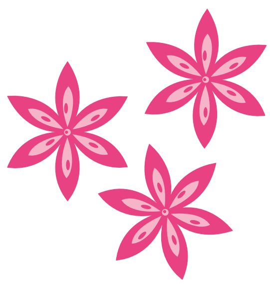
FIGURE 1: The plant helping our fight against flu

Shikimic acid from star anise (*Illicium verum*) is used as a building block to make the semi-synthetic drug oseltamivir (marketed as Tamiflu® and other names), which is used to prevent and treat flu.



Shikimic acid
(from Chinese star anise, natural product)

Oseltamivir
(semi-synthetic product)



provide structural building blocks from which drugs can be produced. A portion of the structure of the drug oseltamivir, used to prevent flu and treat its symptoms, is very similar to a chemical called shikimic acid, which occurs in certain plants. Manufacturing oseltamivir involves extracting this chemical from star anise (*Illicium verum*) and using it as the starting material to synthesise the drug (see Figure 1).

NOVEL APPROACHES NEEDED

The United Nations Sustainable Development Goal 3 is “to ensure healthy lives and promote well-being at all ages”, while the World Health Organization seeks “to achieve universal health coverage, address health emergencies and promote healthier populations”. Despite some successes, we remain a long way from meeting these goals. Cancer, dementia, malaria and other major diseases remain prevalent in society, and the COVID-19 pandemic has clearly highlighted our vulnerability to novel diseases. “We need solutions at hand before facing the future global health challenges,” says Dr Collemare. “Drug discovery and development is such a long process that we need to invest now in prospecting for natural compounds if we want to have these solutions in time.”

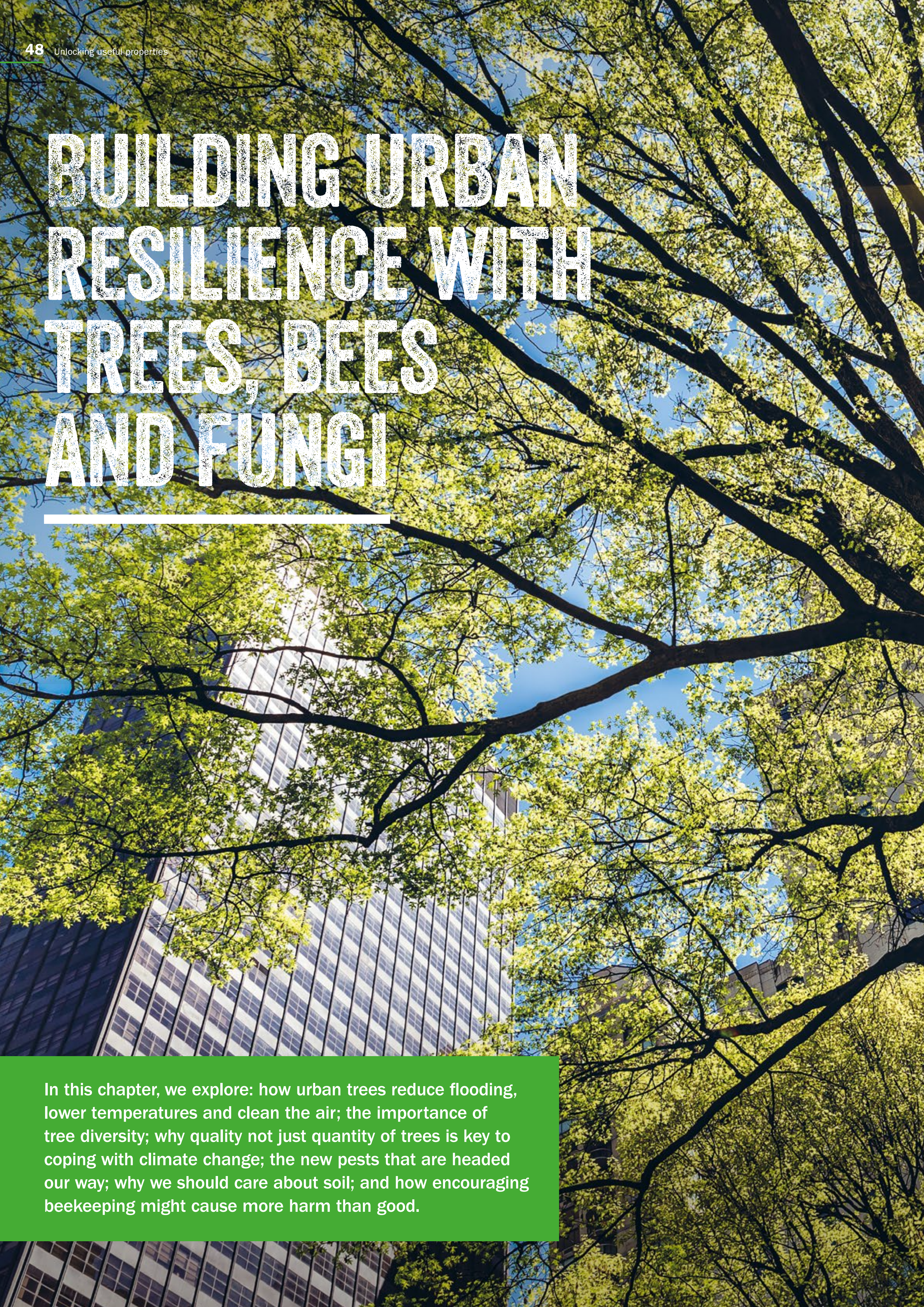
There is great potential to develop new therapeutics from nature in future. Advances in science and technology are providing effective ways to identify useful chemical compounds, source them sustainably, and synthesise them readily.

Even waste could have a role to play in our future healthcare and make the use of our natural resources more efficient; waste from sisal (*Agave sisalana*) leaves following fibre extraction by the textile industry is now being used to make pharmaceutical steroids. Novel approaches and techniques can help us draw inspiration from nature for future medicines, while preserving the biodiversity of our planet.

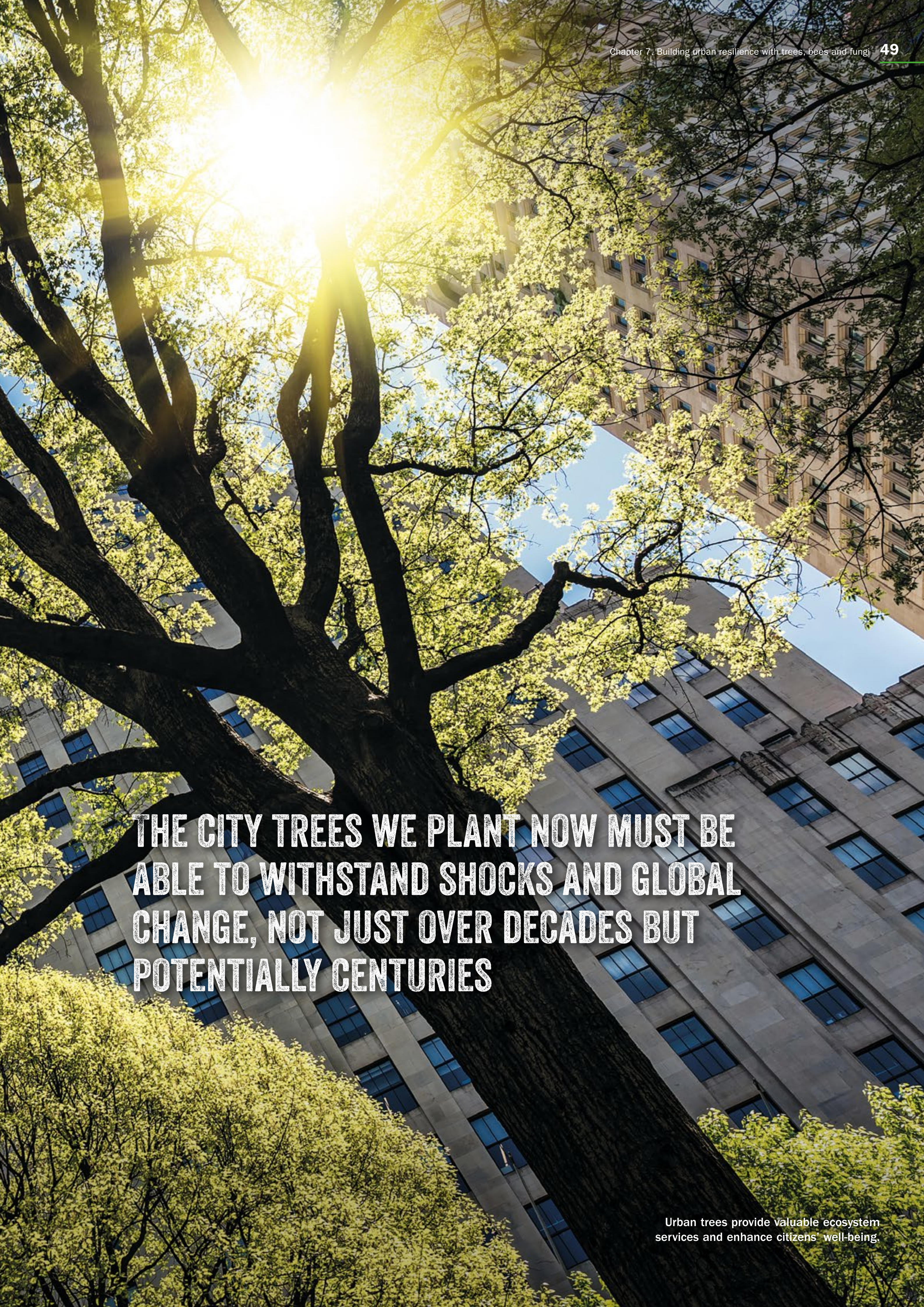
This chapter is based on the following scientific paper published in *Plants, People, Planet*, where you can find more information and references: Howes et al. (2020). Molecules from nature: Reconciling biodiversity conservation and global healthcare imperatives for sustainable use of medicinal plants and fungi. *Plants, People, Planet* 2(5). DOI: https://doi.org/10.1002/ppp3.10138

Read Chapter 7 to find out how ecosystem services from trees, bees and fungi are improving the health of our cities.

BUILDING URBAN RESILIENCE WITH TREES, BEES AND FUNGI



In this chapter, we explore: how urban trees reduce flooding, lower temperatures and clean the air; the importance of tree diversity; why quality not just quantity of trees is key to coping with climate change; the new pests that are headed our way; why we should care about soil; and how encouraging beekeeping might cause more harm than good.



THE CITY TREES WE PLANT NOW MUST BE ABLE TO WITHSTAND SHOCKS AND GLOBAL CHANGE, NOT JUST OVER DECADES BUT POTENTIALLY CENTURIES

Urban trees provide valuable ecosystem services and enhance citizens' well-being.

CITY TREES PROVIDE VALUABLE ECOSYSTEM SERVICES, FROM CLEAN AIR TO FLOOD PROTECTION. ENSURING THEY CAN WITHSTAND CLIMATE CHANGE, PESTS AND DISEASES IN THE FUTURE REQUIRES US TO USE A WIDE RANGE OF SPECIES AND SUPPORT THE INSECTS AND FUNGI THEY INTERACT WITH.

Trees are unsung heroes of our cities. They capture pollutants to clean the air; soften rainfall's impact on soils; reduce flooding by soaking up rain; lower temperatures through shading; and help mitigate climate change by capturing and storing carbon. In the years to come, they have the potential to help make our cities more resilient to what scientists predict will be more variable and extreme weather. However, to ensure we gain the greatest benefit from the ecosystem services trees provide, we must plan our future cityscapes wisely.

The trees growing in cities today tend to be a mix of native and exotic species. In the UK, common native species include silver birch (*Betula pendula*) and English oak (*Quercus robur*), while popular exotics include the sycamore (*Acer pseudoplatanus*) and London plane (*Platanus* × *hispanica*). The presence of non-native species reflects the historical movement of plants around the world by humans, both intentionally and accidentally. For example, the London plane, which is a cross between the American sycamore (*Platanus occidentalis*) and Oriental plane (*Platanus orientalis*), is thought to have arrived with travellers from Spain in the 17th century.

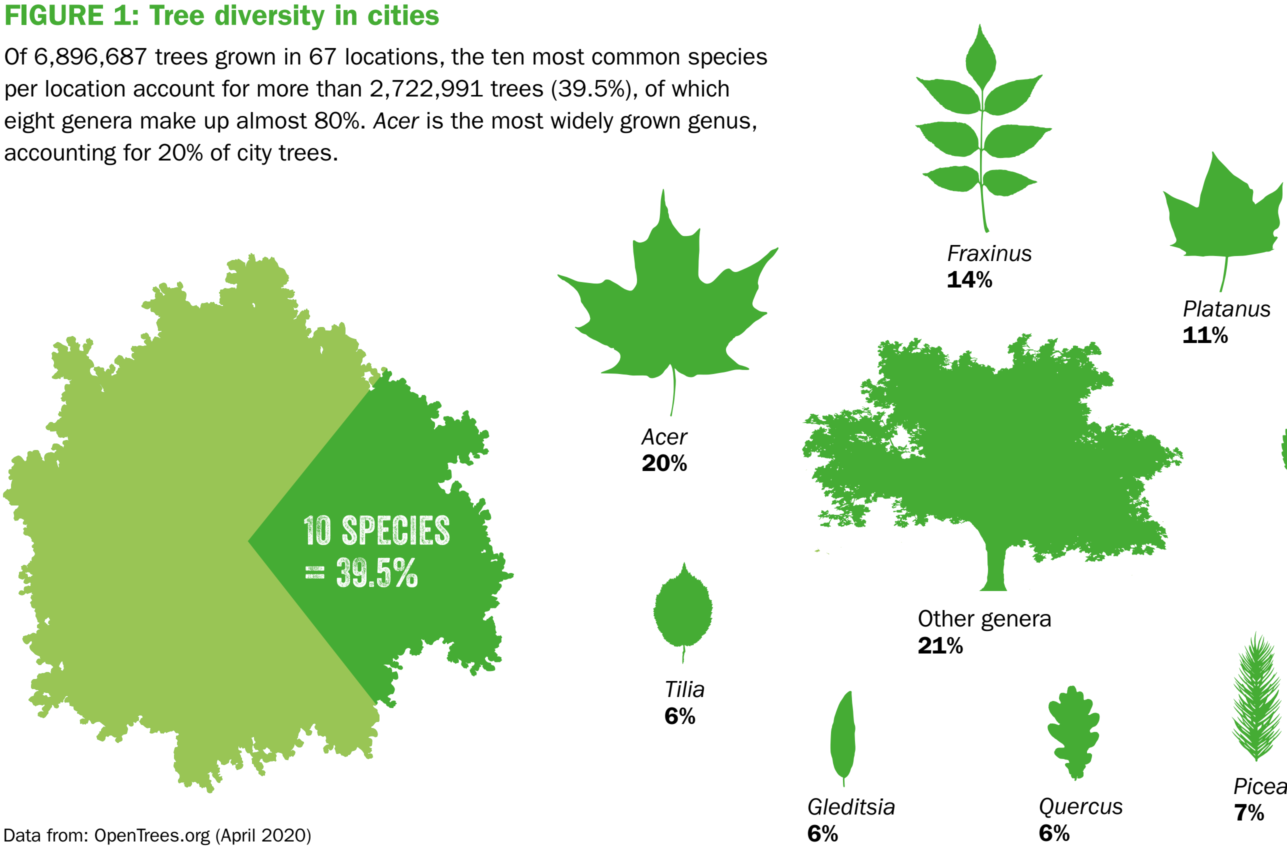
Globally, urban treescapes comprise only a handful of genera, including maple (*Acer*), ash (*Fraxinus*), plane (*Platanus*), elm (*Ulmus*), spruce (*Picea*), oak (*Quercus*), honey locust (*Gleditsia*) and lime (*Tilia*) (see Figure 1). In Scandinavia, *Tilia* × *europaea* and silver birch dominate; in Lhasa, China, poplar (*Populus*) and willow (*Salix*) are the most common genera; and maple species are widespread in US cities. Just five tree taxa account for around a third of trees in London's parks, gardens, playing fields and streets: sycamore, English oak, silver birch, ash and plane.

As well as taxonomic diversity being limited, genetic diversity within species is often low too. This is because specimens grown in nurseries for municipal planting are often clones or derived from limited source plants. However, diversity is key to ensuring our cities' trees are resilient going forward. If we only rely on a few species, with a limited range of genes across individuals, our urban trees will be poorly equipped to survive diseases or pest attacks, or to tolerate changing weather conditions.

The lingering impacts of Dutch elm disease serve as a stark reminder. This beetle-dispersed fungus (*Ophiostoma ulmi*), native to Asia, was accidentally introduced to Europe and the USA in the 1920s. In the late 1960s, at a time when elms were popular urban trees, a new, more virulent strain emerged. Having no resistance to the disease, elm populations outside of Asia were decimated. The UK alone lost 25 million trees, and city tree canopies have yet to fully recover.

FIGURE 1: Tree diversity in cities

Of 6,896,687 trees grown in 67 locations, the ten most common species per location account for more than 2,722,991 trees (39.5%), of which eight genera make up almost 80%. *Acer* is the most widely grown genus, accounting for 20% of city trees.



Data from: OpenTrees.org (April 2020)

Today, new pests are eyeing up our city trees. The Asian and citrus long-horned beetles (*Anoplophora glabripennis* and *A. chinensis*), from South-East Asia, are now among the most serious threats. One estimate of tree loss to *A. glabripennis* in US cities is 30% tree mortality – or 1.2 billion trees – valued at USD 669 billion. Able to thrive on a range of broad-leaved trees and shrubs, these pests present a threat to treescapes globally. Meanwhile, the fungus *Ceratocystis platani* is causing the disease plane tree wilt, which is killing specimens within three to seven years of infection. With planes common in many European cities, losses from the disease could be devastating.

Climate change is also a major threat. Most tree species in cities in the northern hemisphere originated in moist, temperate forests. This makes them less suitable for the warmer, drier conditions forecast for the future. “Our strategies for replacing urban trees that are coming to the end of their life must involve using diverse species lists,” explains Prof. Phil Stevenson, Senior Research Leader in Kew’s Natural Capital and Plant Health department. “The trees we plant now have got to be able to withstand shocks and global change, not just over decades, but potentially over centuries.”

A NEW APPROACH NEEDED

Meeting the demand for robust trees in the future will require changes to sourcing and planting strategies and procedures. Presently, city authorities are primarily motivated by tree-planting targets as a response to climate change. For example, Shanghai, Los Angeles, New York and Sacramento aim to plant between one and five million trees apiece, while London has committed to increasing tree canopy cover by 10% by 2050. But if trees are to survive pests, diseases and climate shifts in future, the focus should be on quality not just quantity of trees.

A starting point for selecting species for future city planting schemes is to assess the ecosystem services that we need in our cities, choose diverse species that can deliver those services, and ensure individuals are genetically diverse (see Figure 2, over page). To do so, we may need to consider rare and less traditional tree species, including exotics. In Scandinavia, for example, it is not feasible to rely solely on native trees for urban green infrastructure, because the region has limited native woody flora, and the majority of those species do not thrive in dry city environments.

The capacity for trees to deliver ecosystem services such as sequestering carbon or reducing impacts from storm waters is species dependent, making careful selection critical. However, levels of tolerance to warmer and drier climatic conditions can also vary within some species. This is especially the case for trees with a large natural distribution; the characteristics of maples, American ash (*Fraxinus americana*) and northern red oak (*Quercus rubra*) populations differ according to rainfall levels and habitat type. This means city tree suppliers will need to have detailed knowledge of the provenance and characteristics of plants in their stocks.

Botanic gardens and nurseries influence the range of urban tree species available to municipal authorities. However, because they have tended to focus on species of ornamental and conservation interest, the ideal genetic stock for developing resilient urban landscapes may not exist in current collections. Remedying this will involve collecting new source stock from the wild, and making species available that have traits such as drought tolerance and disease resistance. These characteristics are controlled by specific genes that could be bred into cultivars for use in urban settings.

“We need to ensure that selected trees have robust genetic architecture that will enable them to tolerate future conditions; it’s no good planting a tree that is currently suitable for Oslo, when in 30 years Oslo will be too hot and too dry for it,” says Henrik Sjöman, Scientific Curator at Gothenburg Botanic Garden, Sweden, who contributed to the review on which this chapter is based. “Ideally, we need to have nursery growers working in concert with laboratories. Most nurseries operate a low-technology system of propagation and cloning but we need more information on genetic diversity, which currently can only be undertaken in well-equipped, state-of-the-art labs. That said, in time, DNA sequencing could potentially be more widely adopted at a much lower cost and used to inform selection of cultivars.”

NURTURING FUNGI TO SUPPORT TREES

As well as considering the trees themselves, we need to give thought to the environments in which we plant them, and the organisms they interact with and depend on. Ninety per cent of all known terrestrial plant species form symbiotic interactions via their roots with naturally occurring fungi in soil, forming ‘mycorrhizas’ (literally, fungus roots). Nurturing this relationship to support trees’ mineral nutrition is therefore critical.

Mycorrhizal fungi increase the volume of soil that trees can explore with their roots; they do so by using their network of filaments (mycelium) to reach into smaller pores, accessing water and nutrients otherwise unavailable to trees. Plants invest up to 20% of the carbon they fix through photosynthesis to support fungi, in exchange for up to 80% of their nitrogen and 100% of their phosphorus needs. This mutual exchange of essential nutrients enhances the productivity and biomass of trees, and strengthens their defences against pests and diseases.

Cities are often harsh environments for plants because of disturbance, pollution, drought, radiation, heat and

PLANTS INVEST UP TO 20% OF THE CARBON THEY FIX THROUGH PHOTOSYNTHESIS TO SUPPORT FUNGI, IN EXCHANGE FOR UP TO 80% OF THEIR NITROGEN AND 100% OF THEIR PHOSPHORUS NEEDS

An oak-lined avenue in Bavaria, Germany. Without a full suite of fungal partners, the ability of trees to thrive in urban ecosystems is compromised.

Oak roots surrounded by a beneficial fungal sheath formed by the oak milkcap (*Lactarius quietus*). These plant–fungal structures are known as ectomycorrhizas (from the Greek for external fungus root).

microclimatic extremes. On top of this, there are often insufficient mycorrhizal fungi in the soil to support plant nutrition and growth. Studies show that mycorrhizal communities vary widely across wild, rural and urban habitats. Atmospheric pollution and ‘eutrophication’ – where soils become overloaded with nutrients from run-off – contribute to the less-diverse communities of fungi in cities. Having suboptimal mycorrhizal nutritional support can compromise a tree’s success in becoming established and its ability to thrive in an urban ecosystem. “Trees are most effective and efficient at providing ecosystem services when they are big,” says Prof. Stevenson. “A big tree sequesters more carbon (especially via its mycorrhizal associations), is capable of trapping more pollution, provides greater flood prevention, can reduce noise pollution, generates a huge amount of pollen and nectar as forage for bees and other insects, and gives more shade. When renewing or establishing new urban ecosystems, therefore, the trees need to become established and grow quickly. The way to do that is to maximise soil quality, especially in the early years, which includes making sure trees have these essential associations with mycorrhizal fungi.”

Supporting mycorrhizal fungi is especially critical because, over time, trees sequester vastly more carbon below ground, via their roots, than they do above it. Trees pump carbon to the mycorrhizal fungi, which extend into the soil with their filaments. The fungi act as carbon sinks in soil, representing up to a third of the soil microbial biomass. Moreover, some mycorrhizal fungi compete with decomposers for the limited resources held in soil organic matter. This suppresses decomposition rates, further boosting the amount of carbon stored in the soil.

FIGURE 2: What urban ecosystems do for us

Overview of the services provided by trees and mycorrhizal fungi in urban ecosystems.

PROVISIONING

Food
Fresh water
Medicines
Raw materials

CULTURAL

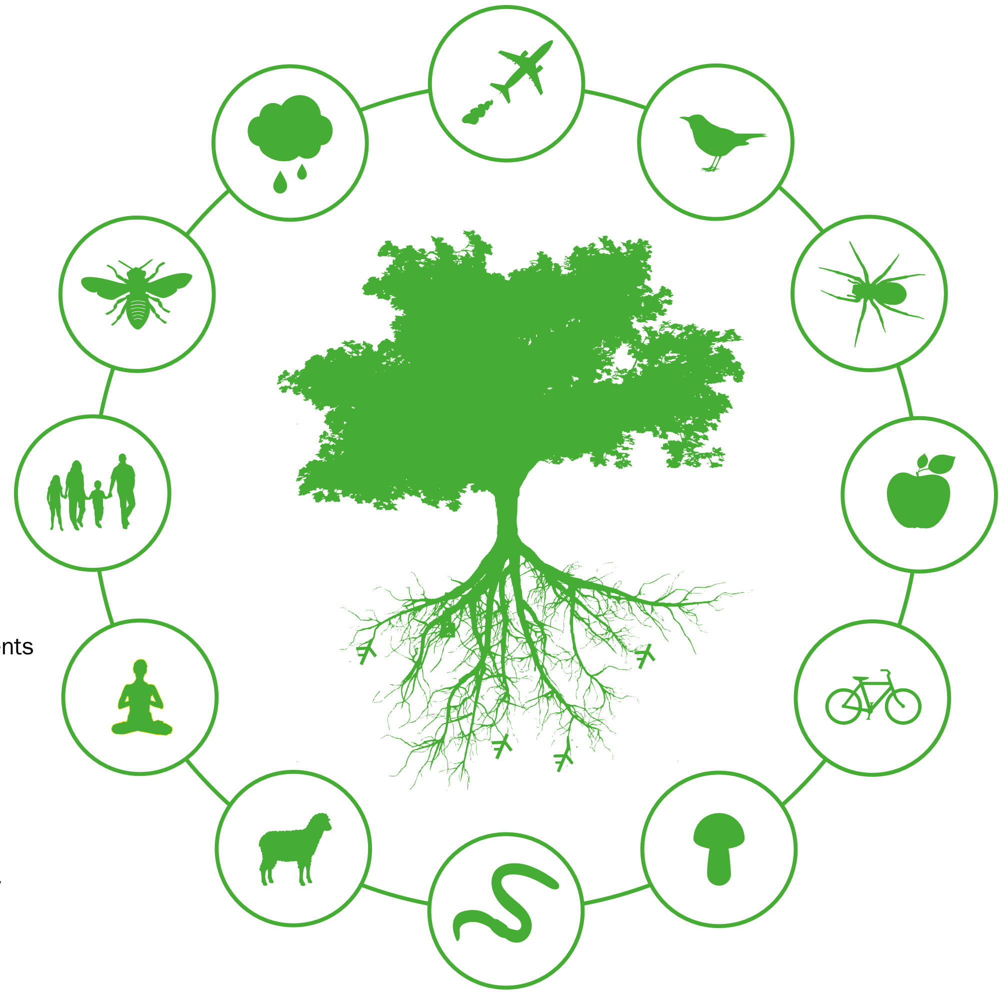
Aesthetic inspiration
Mental and physical health
Recreation
Spirituality and place
Tourism

REGULATING

Air quality and local climate
Carbon storage
Protection from extreme events
Soil improvement
Waste treatment
Biological pest control
Pollination

SUPPORTING

Wildlife habitat and diversity
Genetic diversity



CITIES ARE OFTEN HARSH ENVIRONMENTS FOR PLANTS BECAUSE OF DISTURBANCE, POLLUTION, DROUGHT, RADIATION, HEAT AND MICROCLIMATIC EXTREMES

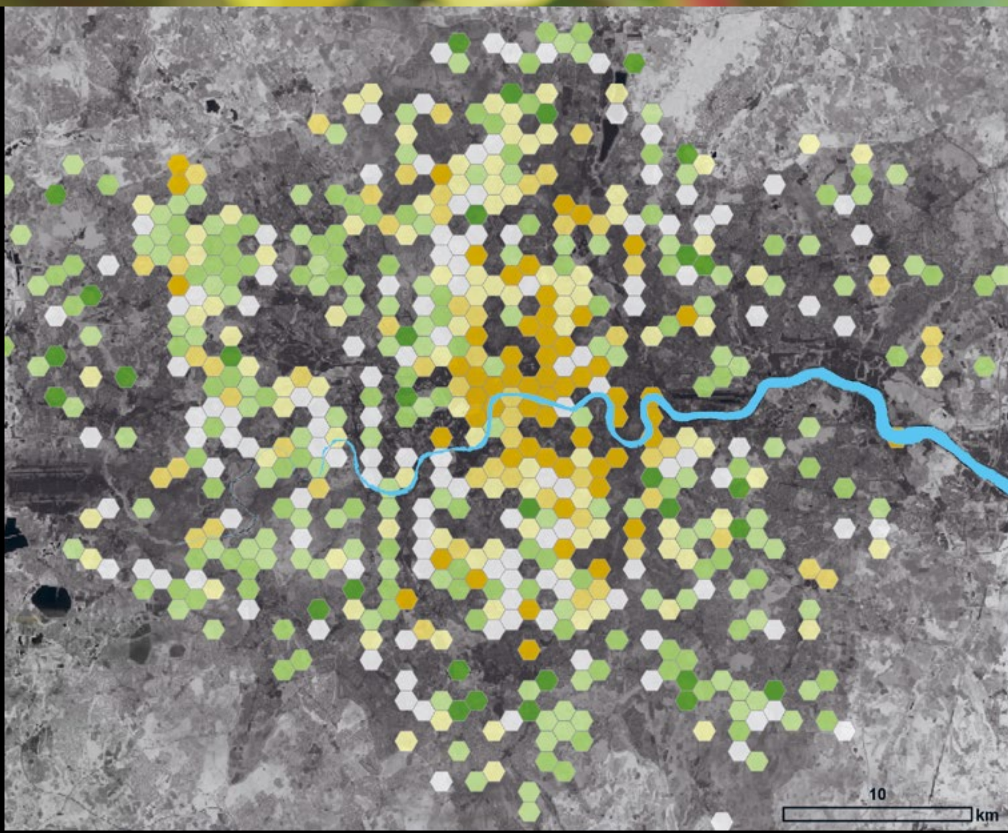
The strawberry tree (*Arbutus unedo*) is an increasingly popular city tree in northern European city parks and provides important nectar resources for wild bees, such as the buff-tailed bumble bee (*Bombus terrestris*), in late summer and early autumn.

FIGURE 3: Green spaces and honey bee colonies in London

Does London have too many honey bees? Recent evidence indicates that 0.13 km^2 of green space is required per colony, or that 1 km^2 can sustain 7.5 colonies. Colour coding identifies the relative forage availability within a grid of 1 km^2 hexagons for each colony, ranging from 1 km^2 foraging area per colony (dark green = surplus) to <0.133 km^2 (dark yellow = unsustainable). In yellow areas, the available forage is insufficient for the honey bee colonies, let alone other competing bee species.

Status of bee forage

- Unsustainable
- Sustainable
- Surplus



We must also consider above-ground interactions in trees, because many tree species depend on pollination by animals. Pollinators, in turn, rely on trees for pollen or nectar as food, and, for some species, as nesting sites. Per unit area of land, trees are able to provide far more nectar and pollen than herbaceous plants, although having a mixture of habitats is beneficial and promotes plant and pollinator diversity.

Arguably the most important group of pollinators globally is bees; worldwide there are over 20,000 species. Ensuring that urban bee populations are healthy can therefore help to underpin the vital ecosystem services that city trees provide and support pollination of nearby crops. In the Neotropics, where tropical rainforest is an important biome, the dominant bee taxa – including stingless bees (*Meliponini*), orchid bees (*Euglossini*), leafcutter bees (*Megachile*) and carpenter bees (*Xylocopa*) – rely heavily on trees for nesting and food.

Presently, assessments of the ecosystem services provided by urban tree species rarely include benefits to bees. The databases used by urban planners either lack data on tree–pollinator interactions or only list whether or not a particular tree species benefits honey bees, rather than considering support for other pollinators. Because some bee species rely on a single or limited number of plants for food, planning decisions that exclude particular species can have drastic consequences on bee populations. We need more detailed research on the value of different urban tree species for bees, to inform planning decisions.

“Some bees are ‘oligolectic’, which means they feed on pollen of just a few species, often within the same genus, which exposes them to greater risk of starvation if their host plant is not available,” explains Prof. Stevenson. “Understanding plant–pollinator relationships is therefore critical for promoting bee diversity. In Europe, most oligolectic species forage on native herbaceous plants, so promoting these plant species is important. And in Australia, many oligolectic bees are pollen specialists of endemic trees and shrubs in the myrtle and protea families (Myrtaceae and Proteaceae); there, trees are critical for supporting bee diversity of potentially at-risk groups.”

SPREADING THE RIGHT WORD

Messages around biodiversity and ecosystem services have not always been clearly communicated. For example, campaigns encouraging people to save bees have resulted in an unsustainable proliferation in urban beekeeping. This approach only saves one species of bee, the honey bee,with no regard for how honey bees interact with other, native, bee species.

In some places, such as London, so many people have established urban hives that the honey bee populations are threatening other bee species. Increasing evidence shows that there is insufficient forage to support current beehive numbers in London (see Figure 3). This is a problem for bee conservation, as honey bees outcompete wild bees by monopolising floral resources. Moreover, some reports suggest honey bees can transmit diseases to other wild species. So, beekeeping to save bees could actually be having the opposite effect.

“In many city parks you’ll see signs telling you about the birds, bats, fungi, trees, grasses and wildflowers that live there, says Prof. Stevenson. “This is fantastic, as positive interactions with nature in cities are known to improve well-being and inspire changes in lifestyles that promote conservation of biodiversity. However, what they don’t say is how all these organisms interact. We need much more information on the interactions and interdependence of organisms, and we mustn’t be afraid to give people more complex information.”

SUPPORTING THE WORLD’S BIODIVERSITY

We need to limit human activities that cause biodiversity loss, because the welfare of people and that of nature are mutually dependent. With more than half the global population now living in urban areas, engaging city dwellers with their local flora, fauna and fungi provides a path to encouraging greater conservation of biodiversity. The hope is that if people see the benefits they derive from urban green spaces in terms of cleaner air, flood protection and enhanced well-being, they will be motivated to help protect biodiversity worldwide for the benefit of humanity as a whole.

This chapter is based on the following scientific paper published in *Plants, People, Planet*, where you can find more information and references: Stevenson et al. (2020). The state of the world’s urban ecosystems: What can we learn from trees, fungi and bees? *Plants, People, Planet* 2(5). DOI: https://doi.org/10.1002/ppp3.10143

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Explore Chapters 8–11 to find out why collections, collaboration and global policy all have a role to play in the exploration of plant and fungal properties.

ENGAGING CITY DWELLERS WITH THEIR LOCAL FLORA, FAUNA AND FUNGI PROVIDES A PATH TO ENCOURAGING GREATER CONSERVATION OF BIODIVERSITY

GETTING THE MEASURE OF GLOBAL COLLECTIONS

In this chapter, we find out: how information stored in collections around the world underpins scientific research; that herbaria alone contain nearly 400 million specimens; how digitisation and data aggregation are widening access to collections; and how linking specimens to DNA samples, images, chemical profiles and other data will help reveal new insights.

SEED BANKS IN
350 BOTANIC GARDENS
IN 74 COUNTRIES
HOLD SEEDS FROM

57,051

SPECIES

The vaults of Kew's Millennium Seed Bank at Wakehurst, UK

A REVIEW OF PRESERVED AND LIVING COLLECTIONS OF PLANTS AND FUNGI AROUND THE WORLD SHOWS THEY ARE A VITAL RESEARCH RESOURCE FROM WHICH WE COULD DERIVE EVEN GREATER VALUE IN FUTURE.

What can a 100-year-old herbarium specimen of twigs and leaves from *Torminalis glaberrima* tell us? To start with, it provides indisputable evidence that in 1920 the wild service tree, as it is also known, grew in the spot from which the specimen was collected. As *T. glaberrima* is an indicator species for ancient woodland, it also provides clues that the site was once wooded. And, if we visit that location today and find a farmer's field, it may reveal information about human activities in the intervening years.

Around the world, specimen collections – including dried plants and fungi in herbaria and fungaria, living plants and fungal cultures grown in botanical gardens and mycological institutes, and seeds stored in seed banks – have long yielded information valuable to science. However, no one had fully investigated the extent of this combined resource. Scientists from Kew, working with a team of international collaborators, undertook a review to find this out. They sought to identify taxonomic and geographical gaps in collections, the extent to which specimens have been digitised, and new collection types needed to support research.

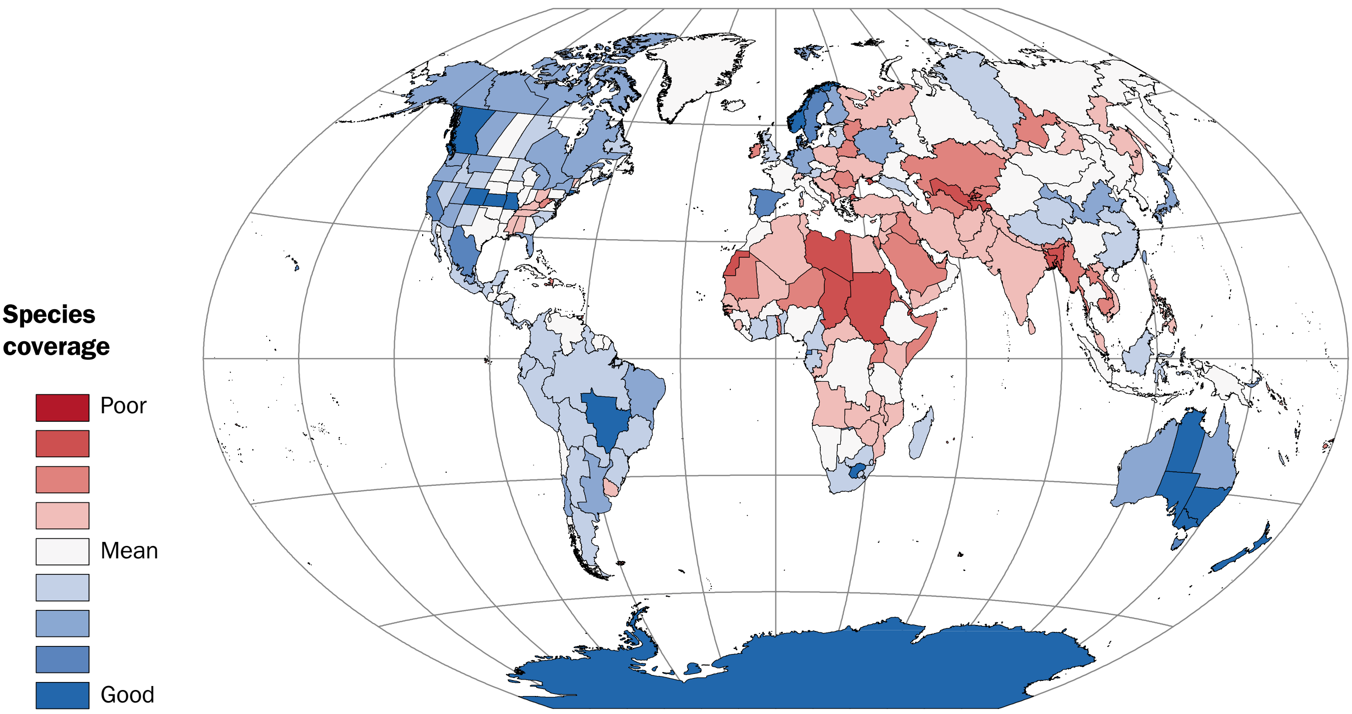
"The world's collections are a unique resource for documenting biodiversity because they give you evidence for what occurred where and when," explains Dr Alan Paton, Head of Collections at Kew. "An individual specimen is an auditable building block, with which you can do all kinds of analyses. The better the state that evidence is in, the more complete the picture we can build of what biodiversity we currently have, as well as what we had in the past, to help us with planning for the future."

REVEALING THE GLOBAL PICTURE

According to Index Herbariorum, there are 3,324 active herbaria in the world, containing 392,353,689 specimens (December 2019). North America (Canada, Greenland, Mexico and the USA) has the most, with 844. However, Europe, with slightly fewer herbaria (828), holds 45% of global specimens. This reflects the European origin of the herbarium tradition – which began in Italy in the 16th century – and the fact that Europe retains many specimens gathered from overseas by colonial explorers. Work is under way to repatriate the information from many of these specimens through digitisation programmes (see also Chapter 9). Temperate Asia (including Russia and China) has the third-highest number of herbaria but the largest number of associated staff, indicating high levels of curation and research.

FIGURE 1: Highlighting gaps in current collections

Mapping the distribution of the collection locations of vascular plant species aggregated in the Global Biodiversity Information Facility, together with data in the World Checklist of Vascular Plants, revealed areas of good and poor coverage. For example, some African countries that are biologically very diverse, are poorly represented in collections data.



The island of New Guinea has 13,634 known species of vascular plants but only a handful of herbaria to document this vast diversity.

"Herbaria, like all natural history collections, not only preserve a record of life on Earth, but foster international collaborations in research, conservation and education," says Dr Barbara Thiers, Patricia K. Holmgren Director of the William and Lynda Steere Herbarium, the New York Botanical Garden, who was part of the Kew-led review team. "Working as a community to share specimens and digitised specimen records and images amplifies the power of these resources for addressing our current environmental challenges."

Some botanically diverse areas have few herbaria. For example, the island of New Guinea has 13,634 species of vascular plants but only five herbaria. By comparison, the UK has only 2,233 native species but 223 herbaria. And although 178 countries have at least one herbarium, many of these collections do not have readily available data showing how many specimens they hold, how many are digitised, and how this information is spread across taxonomic groups (e.g. seed plants, algae, bryophytes, ferns and related groups, and fungi). This restricts our understanding of gaps in collections data and the specimens that have yet to be digitised (see Figure 1). There is also much to be done in training more taxonomists, to allow us to make sense of the vast collections and understand more about biodiversity.

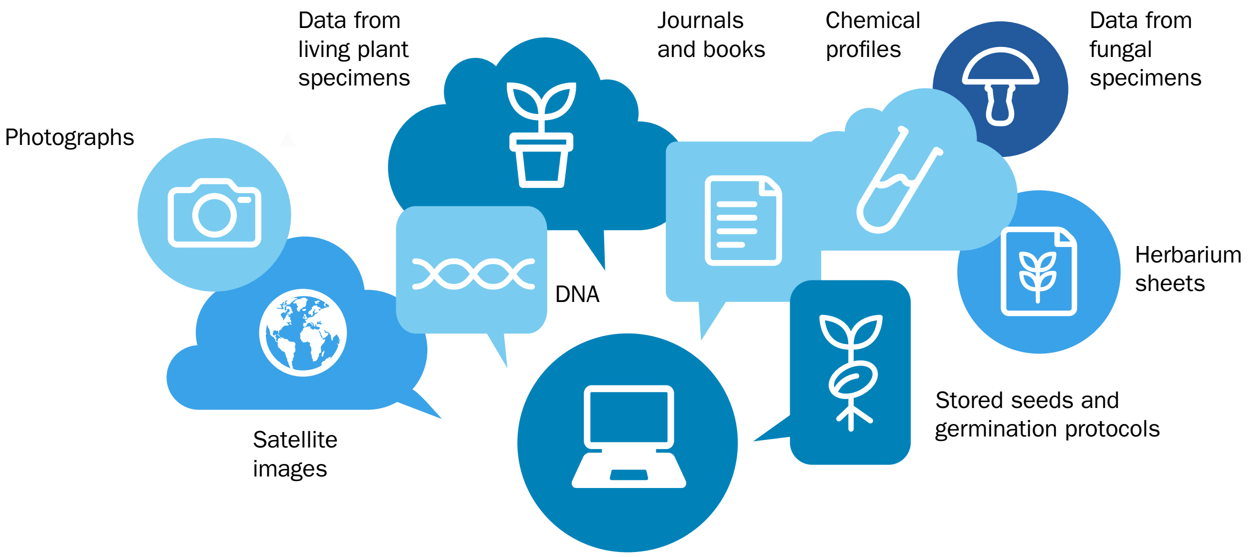
Regarding living collections, analysis of the PlantSearch database hosted by Botanic Gardens Conservation International indicates that 107,340 accepted species grow in botanic garden collections, representing 31% of vascular plant species. However, 93% of these species are held in temperate parts of the world. As a result, a temperate species has a 60% chance of being cultivated within the botanic garden network, whereas a tropical species has only a 25% chance.

Several plant lineages, including bryophytes (the mosses, liverworts and hornworts) and some lineages of vascular plants with clusters of tropical genera, are under-represented in living collections.

107,340 ACCEPTED SPECIES GROW IN BOTANIC GARDEN COLLECTIONS, REPRESENTING 31% OF VASCULAR PLANT SPECIES

FIGURE 2: Making collections accessible to all

The digitisation and aggregation of data on specimens in collections is enabling people around the world to access items from their computers. However, the majority of specimen and collections data remain undigitised.



THE STATE OF SEED BANKING

The Global Strategy for Plant Conservation (GSPC), a programme of the United Nations Convention on Biological Diversity, calls for at least 75% of threatened plant species to be held in *ex situ* collections by 2020, preferably in the country of origin. Such collections include living plants in botanic gardens and seeds stored in seed banks. In recent years, the GSPC target has driven an increase in the number of seed conservation facilities for wild species. Today, at least 350 botanic gardens in 74 countries carry out seed banking. Between them, they have banked seeds from 57,051 species (17% of seed plants). These include more than 9,000 taxa that are globally threatened with extinction, and 6,881 tree species.

Kew's Millennium Seed Bank (MSB) at Wakehurst in West Sussex, holds the world's most diverse store of seeds from wild species. Its success is a product of seed collection by a global network of partners in more than 95 countries, collectively known as the Millennium Seed Bank Partnership. The MSB supports partner countries to establish local seed banks, so that collections can be duplicated in the country of origin and the UK. Around 10% of the species stored in the MSB are extinct in the wild, rare or threatened, and some 20% of taxa are endemic at country or territory level. Seeds of plants from tropical Asia, southern America and the Pacific, however, are presently under-represented.

"The partnership is not close to the target of banking 75% of threatened species yet," says Dr Paton. "There are issues around how we deal with tropical trees, because some very threatened species don't have seeds that can be stored under normal desiccation regimes. Cryopreservation will allow us to do more with seeds and other tissues such as pollen and shoot tips; however, the technique we use with one species might not be transferable to another. So, we also need to think about how else we can reach the target. We may have to consider establishing managed 'seed orchards' as an *ex situ* technique to maintain seed stocks for species that are difficult to preserve."

OVERLOOKED ORGANISMS

Coverage in collections of fungal specimens lags far behind that of plants. Of the 2.2–3.8 million fungal species that scientists believe exist, only 148,000 species have been described and named. Importantly, just over 17% (25,611 species) are cultured and publicly available. Centres registered with the World Data Centre for Microorganisms make available 3.2 million strains of microbes for research, including 849,724 fungal strains. These resources are held in 793 culture collections in 77 countries. However, they are concentrated in Europe (250 collections) and North America (197). Africa, a mega-diverse continent, has only 18 collections.

One issue around preserving fungi is that methods used to isolate individual species from naturally occurring colonies generally favour fast-growing, common fungi. If researchers are to study rare and new organisms, more species need to be available in collections. "There's an area of research emerging that is preserving microbial communities rather than individual species," says Dr Paton. "This is particularly helpful if you're interested in the microbiome [the microbes and fungi] around a tree root. "Because if you only isolate the common taxa, you're only preserving a bit of the available diversity rather than all of it."

Coverage in collections of fungal specimens lags far behind that of plants.

In future, all samples relating to a particular specimen will be digitally linked. For example, a plant in Kew's Temperate House may be linked digitally to DNA samples and chemical profiles, facilitating wider research.

The molecular revolution of recent years has increased demand for samples of tissue and DNA from both plants and fungi. As a result, biodiversity repositories and institutes are increasingly opening up biobanks for preserving tissue (usually leaves from plants and spore-bearing structures from fungi) and extracted DNA. The Global Genome Biodiversity Network coordinates this activity for non-human organisms, across a network of institutions. In doing so, it provides an infrastructure for the global effort to sample DNA and build a full picture of the genetic 'tree of life' on Earth.

ACCESS FOR ALL

Data aggregation is helping to make digital data on collections more widely accessible (see Figures 1 and 2). The Global Biodiversity Information Facility (GBIF) provides anyone, anywhere, with open access to data on all types of life on Earth, encouraging the use of collection data for research. Nearly 2,500 peer-reviewed academic papers have been linked to data providers in the GBIF network, including herbaria and botanic gardens. The facility is therefore adding value to collections and highlighting their importance. Regional data aggregations, including the Atlas of Living Australia and Brazil's Reflora Virtual Herbarium, enhance the use of collections data in specific geographic regions, while also facilitating digital repatriation of specimens.

"Aggregating data has had a huge impact on the use of collections," says Dr Paton. "Imagine if GBIF didn't exist and you wanted to plot where a species grows, you would probably have to consult about ten different herbaria and it would take you a long time, even if they had digital records available. When I started at Kew in 1990, I would have to manually consult the hard copy of the library catalogue or *Index Kewensis* to find data on species. Having online access to literature and specimens, especially aggregated data, means I can do things much faster. I can get a better idea of where things are, and of species variation and distribution."

Despite the progress made through data aggregation, the majority of specimens and collections data remain undigitised. Although GBIF brings together data from 85,576,113 preserved specimens of plants and fungi, this equates to only around 21% of the estimated number of specimens in the world's herbaria. The largest proportion of digitised specimens is from North America; at the other end of the scale, Africa, tropical Asia and the Pacific regions are very poorly represented. And while 95% of vascular plant species and 82% of bryophytes are represented, data are available on only 55% of known fungal species.

The project team's investigation of collections highlights how advances in molecular science, seed banking and digitisation have helped enhance and widen access to accurately named plant and fungal specimens.

However, the gaps and biases revealed show there is great scope for further improvements. Overcoming these demands action, including: governments and aid agencies supporting national collections in biodiverse areas; accelerating digitisation and mobilisation of data through aggregators; standardising nomenclature; collecting taxa from key areas to support national priorities; developing environmental biobank collections to better represent fungal material; providing training in biodiversity science; and researching *ex situ* storage of species with seeds that cannot tolerate the desiccation that is part of the standard seed-banking process.

Making such moves will help scientists draw new data from collections, to address issues such as biodiversity loss and climate change. Today, we obtain information from historic specimens in ways that their original collectors, including the likes of European naturalists Charles Darwin and David Livingstone, would never have dreamed possible. For example, scientists have sequenced DNA from a yam collected in 1782, and other specimens have been used to calculate how carbon dioxide levels in the atmosphere have changed, by examining the density of stomata on leaves. In the future, as-yet-unknown technologies and approaches will facilitate new opportunities, including curating 'extended' specimens, where items in collections are linked to a wide array of data.

"Curators of collections will use specimen identifiers to track and link how material has been used," says Dr Paton. "The idea of an extended specimen means that you will be able to link an image, a DNA sequence and a chemical profile all to a single specimen. How that specimen is then used won't just be limited to someone looking at its physical material; it might be used by researchers interested in its chemistry, collector, cultural value, DNA, or relationships to other species. So it will extend the use of that specimen in different contexts. At the end of the day, the value of collections comes from their use; it's not the fact that you have them, it's the fact that they are used for something that gives them their value."

This chapter is based on the following scientific paper published in *Plants, People, Planet*, where you can find more information and references: Paton et al. (2020). Plant and fungal collections: Current status, future perspectives. *Plants, People, Planet* 2(5).
DOI: https://doi.org/10.1002/ppp3.10141

Read Chapter 9 to find out why collaborations are critical to successful scientific research.

TODAY, WE OBTAIN INFORMATION FROM HISTORIC SPECIMENS IN WAYS THAT THEIR ORIGINAL COLLECTORS WOULD NEVER HAVE DREAMED POSSIBLE

WORKING TOGETHER IS KEY TO A SUSTAINABLE FUTURE FOR ALL

In this chapter, we learn: why collaboration is critical to scientific research; how tens of millions of plant and fungal specimens underpin such work; about the teamwork that created the world's largest virtual tropical herbarium; how Guinea formed partnerships to develop its botanical capabilities; and why farmers in São Tomé and Príncipe are growing fungi.

THE GLOBAL BIODIVERSITY INFORMATION FACILITY PROVIDES ACCESS TO MORE THAN

1.4BN

RECORDS FROM 1,600 INSTITUTIONS

With biodiverse ecosystems, specimen collections, experts and financial resources dispersed around the world, collaboration is critical in scientific research.

THE INFORMATION LOCKED UP IN PRESERVED AND LIVING COLLECTIONS, AND HELD IN EXTANT ECOSYSTEMS AROUND THE WORLD, UNDERPINS OUR UNDERSTANDING OF PLANT AND FUNGAL DIVERSITY. SHARING THIS RESOURCE IN A RESPONSIBLE MANNER IS VITAL TO HELPING US LIVE MORE SUSTAINABLY IN FUTURE.

Globally, institutions hold hundreds of millions of preserved and living plant and fungal specimens. Lined up on shelves in jars of spirits; dried and pressed onto herbarium and fungarium sheets; frozen in seed banks; grown in culture collections; and displayed as thriving exhibits in botanic gardens, they each harbour data on their species' characteristics, favoured habitats and climates, and vulnerabilities. Together, they form the cornerstones of our knowledge of the plant and fungal kingdoms (see also Chapter 8).

With new technologies now available to investigate them, these collections offer huge potential for enhancing our understanding of biodiversity, unearthing useful species and providing nature-based products and approaches to support sustainable development. However, if we are to outpace species loss as we hone our knowledge, we need to expand these collections and make them more accessible. International collaborations that are built on trust and transparency, and underpinned by a workable legal framework, provide the best means to achieve this.

SPECIMENS PAST AND PRESENT

The world's preserved botanical and mycological collections mostly date back to the late 1800s and early 1900s. During this period, extensive European and American exploration led to the publication of many 'Floras', volumes detailing the plants and fungi of particular regions or countries. However, in the past 50 years, significant national collections of preserved plants and fungi amassed by local botanists and mycologists have supplemented the specimens gathered by early travelling naturalists.

Each specimen provides the who, what, when and where for that organism, and can also include descriptions of its form and colour, its habitat, and details of its lifecycle, such as flowering and fruiting time. Collectively, this information can reveal valuable insights into how the distribution of species has changed over time, in response to pressures such as deforestation and climate change. For example, such records show us that the number of plant species on European mountaintops increased fivefold between 1957–66 and 2007–16, a shift linked to rising temperatures.

"Preserved specimens can be 250 years old or more," says Tim Pearce, Conservation Partnership Coordinator at Kew. "You frequently come across collections from the 1800s where a record might say 'large tree, up to 50 feet, found among forest' and then you go back to exactly the same spot and, lo and behold, there is no forest at all, it's just farmland, or urban sprawl. So, these collections give us the opportunity to track the persistence of plant populations at a particular site, over time."

The extent of living collections of wild and cultivated plants has also expanded in recent times. The success of *ex situ* conservation techniques has underpinned the growth of national agricultural and forestry gene banks, along with the more recent creation of conservation seed banks for wild plants, such as Kew's Millennium Seed Bank (MSB). Together, these keep the seeds of tens of thousands of important plant species alive and available for use in the coming decades or even centuries. Meanwhile, botanic gardens around the world have developed their propagation skills and collectively hold many hundreds of thousands of individual living plants; these serve as a huge interpretive resource for millions of public visitors each year. And fungi too, usually held as living isolates, are being successfully conserved and made available to scientists. All these living *ex situ* collections are providing a vital resource for research into medicine, food security and conservation.

TECHNOLOGICAL STRIDES

New technologies for extracting DNA are adding value to herbarium and fungarium specimens, enabling scientists to quickly unravel genetic relationships between species, and publish plant 'phylogenies' or 'trees of life'; the closer two species are on the tree (i.e. the fewer branches connecting them), the more closely they are related. Scientists look for the close relatives of species already in use in agriculture, forestry and medicine that could potentially be developed as new crops or serve as sources of medicinal compounds (see Chapters 3–6). Advances in genomics have made it possible to identify the genes for traits such as high grain yield, the ability to tolerate salinity, and resistance to diseases and pests. This greater genetic understanding is enabling scientists to use living collections to accelerate breeding programmes and enhance the conservation of many useful threatened plant species.

IN THE PAST 50 YEARS, SIGNIFICANT NATIONAL COLLECTIONS OF PRESERVED PLANTS AND FUNGI AMASSED BY LOCAL BOTANISTS AND MYCOLOGISTS HAVE SUPPLEMENTED THE SPECIMENS GATHERED BY EARLY TRAVELLING NATURALISTS

Herbaria such as Kew's hold preserved plant specimens dating back to the 19th century and earlier.

Advances in digital technology, meanwhile, are facilitating the aggregation of datasets. For example, the Global Biodiversity Information Facility (GBIF) provides access to more than 1.4 billion records (including observations, preserved samples, fossils and living specimens) of all types of life on Earth in nearly 53,000 datasets supplied by 1,600 institutions. Plant-focused aggregations include the Botanical Information and Ecology Network, JSTOR Global Plants, and the Australian Virtual Herbarium. Meanwhile, PlantSearch acts as a comprehensive database of plant taxa in botanic gardens and similar organisations. And collaboratively stewarded 'metacollections', detailing the provenance and characteristics of seeds, living plants and tissue samples held in botanic gardens, are also being developed.

TOGETHER IS BETTER

Among the findings of the 2005 Millennium Ecosystem Assessment was that "a major obstacle to knowing (and therefore valuing), preserving, sustainably using and sharing benefits equitably from the biodiversity of a region is the human and institutional capacity to research a country's biota". A challenge is that areas of high biodiversity, biological collections, scientific experts and financial resources are widely dispersed around the planet. This makes it impossible for any one country to work in isolation to describe and sustainably use its plant and fungal resources.

The need to rapidly catalogue, understand, conserve and evaluate valuable plants and fungi has prompted new collaborations to emerge between national and international scientific institutions, governments and local communities. Some recent projects serve to demonstrate the achievements that can be made by bringing botanists, collections, new technologies and local people together. Brazil, Guinea, and São Tomé and Príncipe are among countries that have recently benefitted from powerful scientific collaborations.

Brazil's Reflora programme began in 2010, seeking to "retrieve and make available images and information concerning Brazilian plants deposited chiefly in overseas herbaria" and "increase knowledge and conservation of the Brazilian flora". This involved two parallel efforts. The first digitised Brazilian herbarium specimens in overseas collections and 'virtually repatriated' them in the Reflora Virtual Herbarium (RVH), hosted in Brazil. The second funded opportunities for Brazilian students and researchers to access collections and undertake collaborative research in other countries.

Today, RVH combines 3.7 million digital specimen images sourced from six herbaria in Europe, four in the USA and 72 in Brazil, forming the world's largest virtual tropical herbarium. Half of scientific publications citing Reflora mention conservation, with applications ranging from the rediscovery of a rheophyte (an aquatic plant of fast-moving water) not seen for 170 years, to development of species checklists for use in monitoring and managing protected areas. Another Reflora resource is the List of Brazilian Flora, an online platform hosted by the Rio de Janeiro Botanical Garden, through which 900 scientists from Brazil and elsewhere are collaborating to complete the first online Flora of Brazil.

Factors behind Reflora's success include strong existing relationships between the institutes and scientists involved; a common understanding of the importance of unlocking data from Brazilian herbarium specimens and making it widely accessible; and the choice of a public university with values closely aligned to Reflora's purpose – the Federal University of Rio de Janeiro – to develop the online platform.

"The programme's success is due in part to its broad scope," explains Dr Rafaela Forzza, Herbarium Curator and Senior Researcher at the Rio de Janeiro Botanical Garden, who contributed to the scientific paper on which this chapter is based. "We worked with many different herbaria but accommodated their individual workflows. Obtaining images of specimens deposited in overseas herbaria has long been a dream for many Brazilian botanists – and a dream that's shared is more likely to come true."

In Guinea, achieving positive outcomes for botanical conservation required starting from scratch. Before the current programme began in 2005, most historical botanical specimens collected in Guinea resided in herbaria in Europe and Senegal. Local botanists, having little access to these collections, had limited ability to identify and prioritise areas for *in situ* conservation. The University of Gamal Abdel Nasser (UGAN), working with Kew, recognised that protecting its botanical wealth from an expanding extractive industry demanded a national herbarium and a programme of botanical exploration, which, in turn, called for well-trained scientists.

This led UGAN to establish the Herbier National de Guinée (HNG) and Guinea's Ministry of Higher Education and Research to authorise a new Masters Course in Biodiversity and Sustainable Development. Today, collaborators from both Kew and Belgium's Ghent University contribute to this teaching programme. The partnership resulted in a programme to delineate new protected areas for plants. A national working group on Tropical Important Plant Areas (TIPAs) and Species Conservation Action Plans provided unprecedented opportunities for academics, government staff and non-governmental organisations to collaborate on plant conservation, and, in March 2019, led the government to commit to protecting 22 TIPAs. This unlocked new funding opportunities, including a grant to conserve Guinea's Critically Endangered national flower *Vernonia djalonensis*.

"OBTAINING IMAGES OF SPECIMENS DEPOSITED IN OVERSEAS HERBARIA HAS LONG BEEN A DREAM FOR MANY BRAZILIAN BOTANISTS – AND A DREAM THAT'S SHARED IS MORE LIKELY TO COME TRUE"

Brazil has formed the world's largest tropical herbarium, using digitised specimens from physical collections in 82 herbaria.

Engaging local people, who are the true custodians of ecosystems, is vital for effective conservation.

"The long-term collaboration with our partners at the Royal Botanic Gardens, Kew, has re-invigorated the research and conservation of Guinea's plants, and raised the quality of our training to a new cadre of young national botanists on modern approaches to taxonomy and plant identification," says Dr Sékou Magassouba, Director General of the HNG, who was also an author on the paper. "Through our databases and by publishing the book *Threatened Habitats and Tropical Important Plant Areas (TIPAs) of Guinea, West Africa* – the first of its kind in Africa – we have mobilised important scientific data, ensuring they are integrated into decision-making for national biodiversity priorities."

To be truly effective, conservation programmes need to engage local people, as they are the real custodians of species and ecosystems. In São Tomé and Príncipe, which is a renowned global biodiversity hotspot, foreign institutes had made many new discoveries of fungi over the years but there was little recognition of the value of these findings among islanders. In 2019, a collaboration between the University of Coimbra, Portugal, and the island nation's Directorate General of Forests set out to fill this gap.

São Tomé and Príncipe's forest resources are under pressure from its growing population, and in future, as woodlands continue to be depleted at lower altitudes, small farmers are likely to be forced to move to higher elevations. Most endemic fungi occur on higher ground, so the collaboration sought to develop markets for edible and medicinal mushrooms, and train farmers in green economy and entrepreneurship. So far, several genera of known species with potential for domestication have been identified. "Improving people's livelihoods through a resource that is part of their natural heritage is the best way to develop a sense of pride, ownership of and responsibility for the continued sustainable management of that resource," says co-author Dr Susana Gonçalves, who is the project's leading mycologist and works closely with the local island communities. "This community-led approach, only possible with the partnerships in place, is paving the way for an enduring solution to forest and fungi conservation in São Tomé."

SHARING RESOURCES IS KEY

All collaborative international conservation programmes have one thing in common: their need to access and share biological genetic material across the world. The legal framework through which this is presently managed is the Nagoya Protocol of the Convention on Biological Diversity (CBD). However, some scientists have criticised the protocol for stifling the sharing of material for research programmes (see also Chapter 10). For example, concerns have been raised that the protocol does not sufficiently differentiate between commercial and non-commercial research uses, and that there are not robust methods in place for tracking resources to ensure that material loaned for pure research purposes does not end up being exploited commercially. This has made some countries wary of sharing any material.

"The Nagoya Protocol set out to make sure that the benefits accruing from somebody like me going out and collecting genetic material – whether those benefits accrue to me as a researcher, to the science community or the common good – should be shared equitably with the country of origin," explains Kew's Pearce. "There are challenges throughout this process. At the beginning of any new partnership, it can take a long time to reach a set of terms that parties at all levels agree on. In the early 2000s, when we were establishing Kew's global MSB Partnership programme, the time taken to negotiate agreements was often measured in years rather than months. But it has to be said that the process developed trust and mutual respect between the partners. The long-term benefit of growing these relationships into lasting collaborations has been immense."

One approach that avoids unnecessary delays is that adopted by the International Treaty on Plant Genetic Resources for Food and Agriculture. This agreement, which also works in harmony with the CBD, seeks to promote the "conservation and sustainable use of plant genetic resources for food and agriculture, and the fair and equitable sharing of the benefits arising out of their use". The Treaty covers 64 major food and forage crops, guaranteeing farmers, plant breeders and scientists timely access to genetic material related to these crops.

UNCOVERING VITAL EVIDENCE

The United Nations (UN) Sustainable Development Goal (SDG) 17 highlights the need for national, regional and international collaboration to support many of the other SDGs, which are due to be achieved by 2030. Meanwhile, a 2019 report by an independent group of scientists appointed by the UN Secretary-General stresses that: "no country is yet convincingly able to meet a set of basic human needs at a globally sustainable level of resource use". Fulfilling such goals under current political landscapes and governance structures is a tall order. However, if scientists can work quickly to decode the messages stored in collected and wild specimens, and provide leaders with evidence that might trigger action, we will be better placed to deliver a sustainable future for all.

This chapter is based on the following scientific paper published in *Plants, People, Planet*, where you can find more information and references: Pearce et al. (2020). International collaboration between collections-based institutes for halting biodiversity loss and unlocking the useful properties of plants and fungi. *Plants, People, Planet* 2(5). DOI: https://doi.org/10.1002/ppp3.10149

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Read Chapter 10 to find out how the legal mechanisms used to protect natural resources can both help and hinder scientific research.

DOES CONSERVATION POLICY HELP OR HINDER SCIENTIFIC RESEARCH?

In this chapter, we explore: the aims of the Convention on Biological Diversity and the Convention on International Trade in Endangered Species of Wild Fauna and Flora; whether these legal mechanisms are stifling scientific research; the Nagoya Protocol's effectiveness in encouraging countries to share genetic resources; and the need for robust compliance systems.

>30,000

PLANTS SPECIES ARE PROTECTED UNDER CITES

The Convention on International Trade in Endangered Species of Wild Fauna and Flora

Scientific research depends on nations sharing material, which requires effective legislation.

INTERNATIONAL CONVENTIONS ON BIOLOGICAL DIVERSITY AND TRADE IN ENDANGERED SPECIES SEEK TO SUPPORT RESEARCH, PREVENT HARM TO SPECIES AND ECOSYSTEMS, AND BENEFIT SOURCE NATIONS AND LOCAL COMMUNITIES. A NEW REVIEW SUGGESTS ALIGNING IMPLEMENTATION APPROACHES COULD MAKE THESE MECHANISMS MORE EFFECTIVE.

With biodiversity loss quickening, we need to step up efforts to name, classify, describe and protect species before they become extinct. If we do not, we may lose useful plants and fungi before understanding their true value. Conducting this work requires extensive international collaboration (see Chapter 9) and a global policy framework that encourages the sharing of scientific material. This is because the biodiverse ecosystems, specimen collections, scientific experts and financial resources needed to underpin research into biodiversity are widely dispersed around the planet. A functioning legal framework through which researchers can access and undertake research on plant and fungal resources, and which prevents exploitation of valuable genetic material, is therefore critical.

Legal mechanisms already exist to control the movement of genetic material around the globe. These include the Convention on Biological Diversity (CBD) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). They aim to protect vulnerable species and ecosystems, and promote the sustainable use of resources. However, some studies had suggested these mechanisms might be stifling research. In response, an international team of collaborators, led by Kew, set out to assess how effective the Conventions have been in supporting the scientific research vital to achieving their goals.

Focusing on the kind of investigations that plant and fungal experts conduct – involving taxonomy, seed biology, genomics, ecological interactions, ecosystem services, and the effects of climate change – the researchers examined how helpful the mechanisms within the CBD and CITES are in supporting non-commercial research. Their findings suggest that recent moves to make the Conventions more research-friendly are beginning to have a positive effect, but that there is room for further improvement.

HALTING GLOBAL BIODIVERSITY LOSS

The CBD was agreed in 1992, with the aim of tackling global biodiversity loss. Its three objectives are: the conservation of biological diversity; sustainable use of biodiversity; and the fair and equitable sharing of benefits arising from use of genetic resources. The Convention's Access and Benefit-Sharing (ABS) mechanism was intended as an incentive for countries to invest in conservation (see Figure 1). As such, it was a key reason why many of the 196 Parties (countries that are signatories to the CBD and have also committed to implement its objectives at a national level) ratified the Convention, particularly those with high biodiversity.

The CBD recognises the rights of countries to manage their own natural resources and introduce legislation to control access to genetic resources. In an effort to encourage governments to smooth the way for non-commercial research, it required Parties to 'create conditions to facilitate access to genetic resources for environmentally sound uses'. However, the different ways in which countries interpreted the CBD led to criticism that overly complex legislation was hampering research. And with less research taking place, countries were failing to reap the anticipated benefits needed to support national conservation efforts.

"Countries began to introduce a range of legislation," says China Williams, Senior Science Officer in Science Policy at Kew. "Non-commercial users of genetic material, such as botanic gardens and research institutes, often had to go through complex mechanisms to access specimens for research, and commercial companies weren't always sure if they had legal certainty that they could use or develop material. Crucially, the biodiverse provider countries weren't getting the benefits they expected. As a result, there were calls for a more legally binding way of approaching the benefit-sharing part of the Convention."

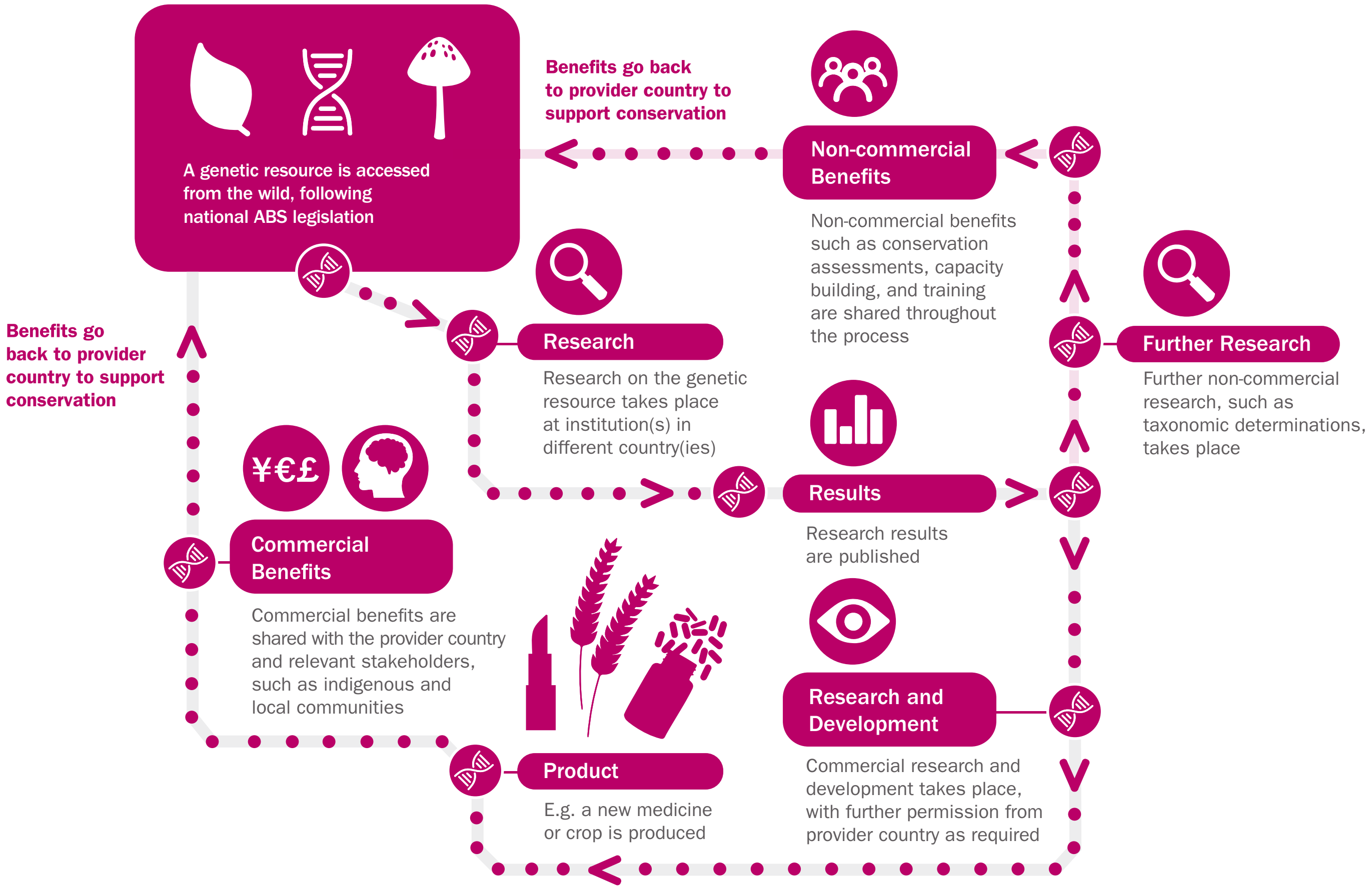
The outcome of discussions was the Nagoya Protocol. Negotiated by Parties to the CBD and adopted in 2010, the Protocol came into force in 2014. This guided countries on how to frame access legislation and introduced a legally binding compliance regime to enforce benefit-sharing. Importantly, it sought to address criticisms of the complexity of ABS legislation by encouraging Parties to implement "simplified measures on access for non-commercial research purposes".

Now emerging from its bedding-in phase, the Nagoya Protocol calls for Parties to encourage the development and sharing of codes of conduct, guidelines and best practices or standards in relation to ABS. To ensure compliance with national legislation, it states that Parties should issue a permit as evidence that they have granted access based on prior informed consent and mutually agreed terms. On issuing a permit, a country must upload the relevant details to an online Access and Benefit-Sharing Clearing House (ABSCH), which produces an Internationally Recognized Certificate of Compliance (IRCC) in return.

HELPING OR HINDERING RESEARCH?

To assess the effectiveness of the CBD and Nagoya Protocol in promoting research in biodiversity, the Kew-led research team analysed ABS measures in 20 countries, including at least one on each continent (excluding Antarctica). They consulted the ABSCH to identify trends in access to material and see which countries, if any, had introduced measures intended to simplify access to genetic material. And they examined patterns in the issuing of IRCCs.

FIGURE 1: Access and Benefit-Sharing (ABS) in action



Of the 20 countries assessed, 11 had put in place simplified measures, with France, Spain, the Republic of Korea and the Dominican Republic doing so following ratification of the Nagoya Protocol. Beyond these 11, Namibia, Ethiopia, Malaysia and Vietnam had introduced simplified access measures but only for research taking place in country, for national researchers or researchers based at national institutions. In Brazil, access was simplified for some types of research but not for the fundamental, non-commercial research that forms the bedrock of biodiversity science. Kenya, the Philippines and Uganda had not introduced any simple access measures. And one country, Japan, had not put access measures in place.

The case of Brazil exemplifies the kinds of challenges arising where simplified access to resources is not available for conducting basic research. Having greater biodiversity than any other nation, with 55,000 known species of plants alone, Brazil is a hotspot for plant and fungal research. While not a Party to the Nagoya Protocol, it has introduced ABS legislation to regulate access to genetic heritage (including both information and physical material) for research, technological development and economic exploitation of products.

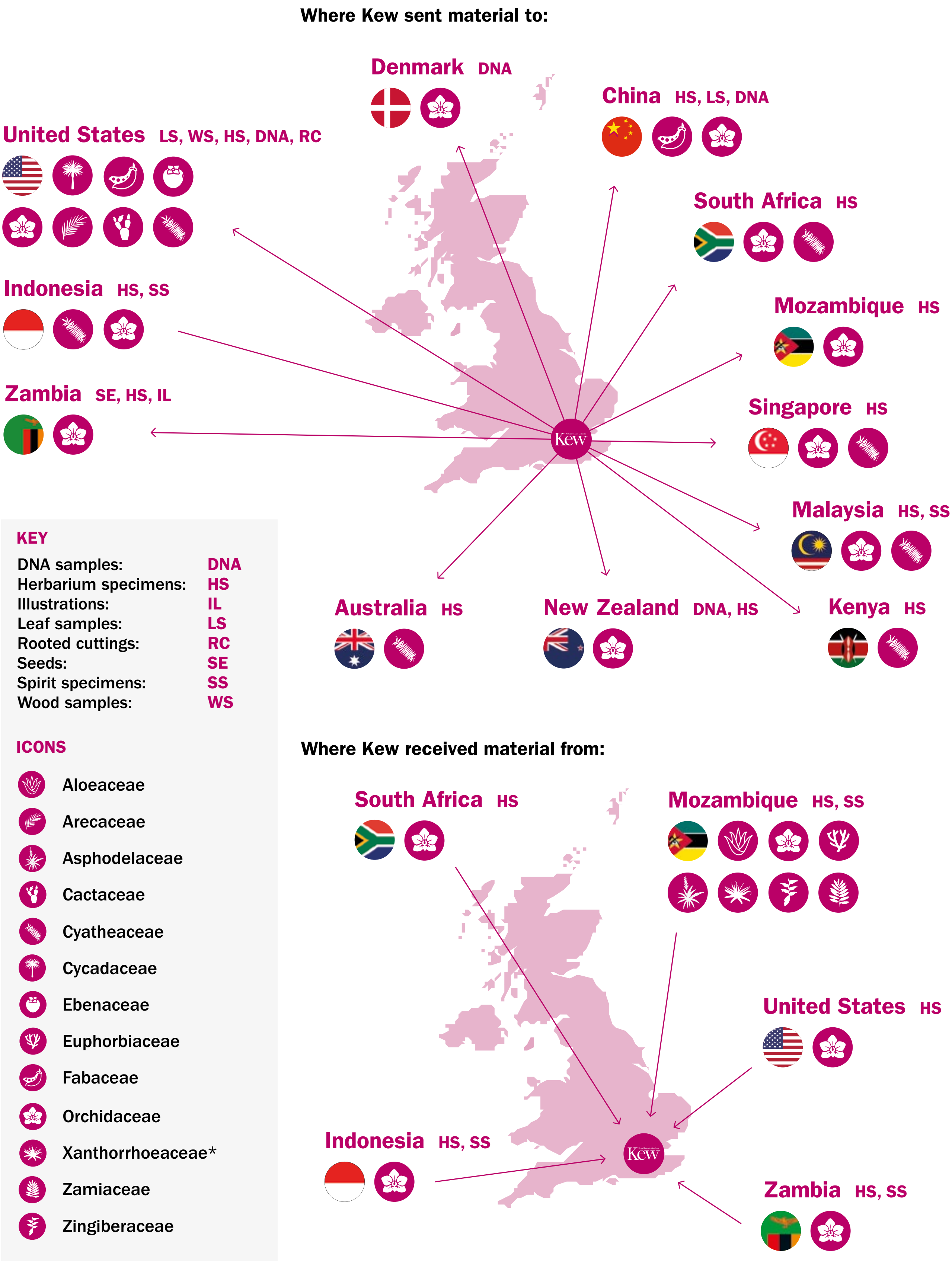
All research must be registered on an electronic system, with foreign researchers having to be associated with Brazilian institutions. However, some researchers have reported that they have been prevented from publishing descriptions of new bacterial species because they have been unable to reconcile the requirements of the International Code of Nomenclature of Prokaryotes with Brazil's strict laws on the sharing of material.

"In my opinion, the decision to require foreign researchers to collaborate with Brazilian institutions aims to promote more scientific development in the country. However, while this requirement may make sense in cases of applied research and technological development, in the case of basic research it has a negative result for Brazilian science, as we have been witnessing," says Dr Manuela da Silva, Director of Biological Collections at Fiocruz, Brazil, who was part of the Kew-led research team.

The reluctance of some countries to introduce simplified access measures to cover all research taking place suggests they may have concerns over being able to track and control material once it has left their shores. Overcoming this would require compliance procedures in the user country that are trusted by the provider country. "Lack of transparency and legal certainty that ensure compliance in the user country are among major concerns for provider countries, which often lack both the financial and technological capacity to effectively follow up on agreed terms and conditions, and to track their genetic resources and associated knowledge," says Dr Gemedo Dalle, Associate Professor of Addis Ababa University, Ethiopia, and former Minister for Environment, Forest and Climate Change of the Federal Republic of Ethiopia, who also contributed to the study.

FIGURE 2: Where Kew sent specimens to and received them from, under the Convention on International Trade in Endangered Species of Wild Fauna and Flora, during 2014–2019

These data include exports and imports of non-commercial specimens to and from Registered Scientific Institutes only.



*Now in Asphodelaceae (Angiosperm Phylogeny Group IV)

Specimens arrive at Kew from all over the world. Robust tracking of biological material is critical for compliance with international conventions.

Coco de mer (*Lodoicea maldivica*), which only grows in the wild in the Seychelles, is protected under Appendix III of CITES.

Biological specimens from around the world are vital to Kew and partners' research into biodiversity.

In the UK, a Party to the Nagoya Protocol, there has been a compliance procedure in operation since 2015, and sanctions for non-compliance. Users are required to comply with the regulations in force in the UK; awareness-raising and active enforcement is ongoing.

In terms of IRCCs, the researchers found that the number of certificates had more than doubled to 1,192 in the six months prior to 1 February 2020. Eight of the 20 focal countries had registered IRCCs, representing 95% of all certificates uploaded. Of the total certificates, 59% were for non-commercial purposes and 41% for commercial uses. “I think it is a good sign that the number has risen,” says Williams. “It shows that countries are engaging with the process and also have the capacity to use it.”

REGULATING TRADE IN VULNERABLE SPECIES

Introduced in 1975, CITES regulates international trade in wildlife and wildlife products – ranging from plants and food, to leather goods and souvenirs. Its aim is to prevent international trade from threatening the survival of wild plants and animals. As of 2019, it had 183 Parties and covered roughly 30,000 species of plants. Fungi are also covered but, as yet, no species have been listed. As with the CBD, Parties abide with CITES regulation by implementing legislation in their own countries.

Three Appendices denote different levels of protection from trade, based on the threat from commerce to the organism concerned. Appendix I includes species in danger of extinction from international trade, for example Rothschild’s slipper orchid (*Paphiopedilum rothschildianum*); international trade for commercial use is prohibited for all Appendix I species. Appendix II includes species that are not currently threatened, such as the big-leaf mahogany (*Swietenia macrophylla*), but which may become so if trade is not monitored. Trade in these species requires a permit. Appendix III includes species that are protected in at least one country and where the government concerned has requested help to support their regulation, for example the coco de mer palm (*Lodoicea maldivica*).

To accommodate the needs of non-commercial research, CITES established the Registered Scientific Institute (RSI) Scheme. Countries are encouraged to register RSIs; these organisations can share material freely with each other without requiring permits (see Figure 2, pg 76). So far, 74 Parties have registered a total of 857 scientific institutions with the CITES Secretariat. Between 2014 and 2019, Australia, Austria, Denmark, Italy, Germany, Spain and the UK all registered new scientific institutions, from one RSI registered in Denmark to 17 in Australia.

A BOON OR BOTHER TO RESEARCHERS?

To assess the effectiveness of the RSI scheme, the researchers sent questionnaires to CITES Management and Scientific Authorities within the 20 study countries, as well as EU member states[1]. They requested annual reports and information on the performance of the RSI scheme.

Overall, responding Parties felt that while it was important to register institutions involved in species conservation, it was difficult to use the scheme or interpret its language. For example, the scheme could not be used where CITES was not implemented in both countries involved in the exchange of material. Some respondents felt it was easier to apply for a one-time permit than obtain material via the scheme.

“As with the Nagoya Protocol of the CBD, it is left up to individual countries to decide on criteria for registration,” says Dr Carly Cowell, Senior Science Officer for CITES at Kew. “So, some countries might only allow national bodies to be RSIs; others permit private organisations. Some might charge; others might not. In the UK, organisations have to provide the government with a full list of their collections, and information on how they are managed, stored and kept secure.”

NO TIME TO WASTE

Time is running out for us to understand and conserve the world’s immense biodiversity. If we are to speed up cataloguing of resources, scientists working around the globe need to be able to continue undertaking research on genetic material. The investigation by Kew and partners shows there is widespread acceptance of legal frameworks such as the CBD, Nagoya Protocol and CITES. However, more must be done to encourage countries to embrace these Conventions, and for them to work effectively.

Nurturing greater trust at government level among Parties requires robust compliance systems, while standardised application systems would make life easier for the end-user scientists. “I’m pleased to see increased recognition of the need for clear, transparent online systems where there is simplified access for non-commercial research,” says Williams. “I think that will encourage research in CITES-listed and non-listed species and their use, and through this should come increased benefits. You don’t get benefits without use, and the mark of success is seeing benefits from the research going back to the countries of origin.”

This chapter is based on the following scientific paper published in *Plants, People, Planet*, where you can find more information and references: Williams et al. (2020). Conservation policy: Helping or hindering science to unlock properties of plants and fungi? *Plants, People, Planet* 2(5). DOI: https://doi.org/10.1002/ppp3.10139

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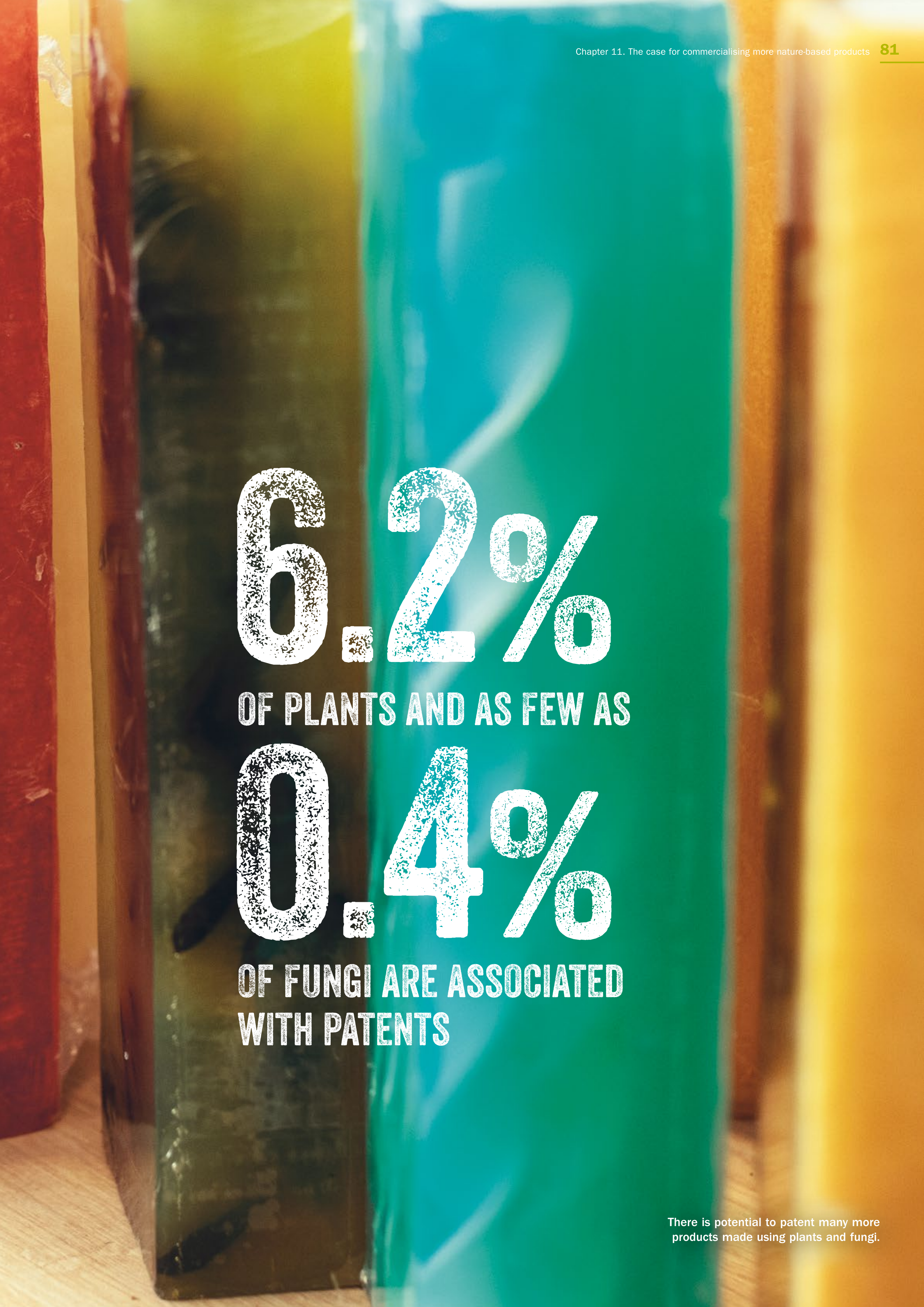
Read Chapter 11 to find out how better patenting procedures could help us to commercialise and conserve natural resources.

[1] At the time the study was conducted, the UK was a member of the EU.

THE CASE FOR COMMERCIALISING MORE NATURE-BASED PRODUCTS

In this chapter, we investigate: why so few plants and fungi have patents associated with them; successes and failures of the patenting system; India's multidisciplinary approach; and how patenting nature-based products can generate wealth, reduce poverty, enhance human well-being and encourage conservation.



6.2%

OF PLANTS AND AS FEW AS

0.4%

OF FUNGI ARE ASSOCIATED WITH PATENTS

There is potential to patent many more products made using plants and fungi.

ONLY A SMALL PERCENTAGE OF THE PLANTS AND FUNGI THAT EXIST ON EARTH ARE ASSOCIATED WITH PATENTS. KEW AND COLLABORATORS SOUGHT TO IDENTIFY THE BARRIERS THAT ARE HOLDING BACK GREATER NATURE-INSPIRED INNOVATION.

Humanity evolved using plants and fungi for food, medicines and materials, but over the millennia the number of widely used species has dwindled. As other chapters in this report show, the number of plants and fungi we rely on for food and renewable energy, in particular, is a fraction of what it could be. With 347,298 known vascular plant species and potentially upwards of 2.2 million fungal species on the planet, this represents a missed opportunity. Not only could we all stand to benefit from new products, but the commercial use of our natural resources might help to incentivise their conservation at a time when biodiversity loss is accelerating.

Kew and an international team of collaborators set out to investigate the number of plants and fungi in commercial use, using patents as a proxy for innovation. They aimed to explore the extent to which we are utilising our natural resources and identify barriers that might be limiting nature-based product innovation. “We chose to examine the use of natural resources through the eyes of patents because that is a clear step to commercialisation,” explains Prof. Monique Simmonds, Deputy Director of Science at Kew. “When I started the project, I had envisaged we might use around 20% of known plant and fungal diversity, but the proportion is actually much, much smaller than I thought.”

To find the exact figure, the research team consulted a 2013 publication in the journal *PLOS ONE* (published by the Public Library of Science) entitled, ‘Biological diversity in the patent system’. The authors of this publication reviewed 11 million patent documents from the USA, the European Patent Convention and the International Patent Cooperation Treaty published between 1976 and 2010. After cleaning and harmonising Latin names, they found that 26,111 species of plants and 7,918 species of fungi were associated with patents. Further removal of ambiguous plant names by the Kew-led research team reduced the number of plant species to 21,395.

Prof. Simmonds and colleagues divided these figures by the numbers of known species of vascular plants (347,298) and fungi (148,000) to derive the percentages associated with patents. For plants, the result was 6.2%, and for fungi, 5.4%. Using the 2.2 million estimate for the calculation brought the percentage of fungal species linked to patents down to 0.4% (see Figure 1).

“I think it is a real shame that more plant- and fungus-derived materials aren’t subject to appropriate patents, because it would increase the economic value of biodiversity,” says Prof. Simmonds. “More people would realise the potential plants and fungi have, because many of those patents would have resulted in some form of commercialisation. And provided appropriate systems were in place, that would result in money going back to the place where the biodiversity came from.”

HOW PATENTS WORK

The basic principle for patenting an innovation is that it must be new, involve an inventive step and be capable of development through industry. A patent endows its owner with the legal right to exclude others from making, using or selling their invention for a defined period of time. In exchange, the owner of the intellectual property must set out the details in a publicly available document. There is currently no universal patent available; parties must therefore file patents in individual countries for international coverage.

The rules around use of genetic material are guided by the Convention on Biological Diversity (CBD). Agreed in 1992 and ratified by 196 Parties, the CBD seeks, among other objectives, the fair and equitable sharing of benefits arising

FIGURE 1: The percentages of plants and fungi associated with patents

Considering the human race evolved using plants and fungi as foods, medicines and materials, relatively few species are used in patented commercial products.

Number of vascular plant species
347,298 (known)

Number of fungal species
148,000 (known)
to >2.2 million (estimated to exist)

Pelargonium sidoides

Aspalathus linearis

Hoodia gordonii

The patenting process has sometimes been controversial, as these examples show:

Pelargonium sidoides featured in a patent for a product treating upper respiratory infections. When challenged, the patent was revoked due to “lack of an inventive step”.

Since 2010, Africa’s indigenous San and Khoi organisations have demanded that patents associated with the use of *Aspalathus linearis* for rooibos tea recognise the role their indigenous knowledge played in the drink’s development.

Mesembryanthemum tortuosum (formerly *Sceletium tortuosum*)

Eragrostis tef

Properties from *Sceletium tortuosum*, traditionally used as a mood enhancer, were patented without the consent of San traditional healers who had contributed knowledge. A benefit-sharing agreement was later signed to pay royalties to the San.

Patents filed for use of the plant *Carapa guianensis*, from Brazil, were later rejected due to ‘prior art’, because the patents covered uses that already existed.

Patents applied to the Ethiopian plant *Eragrostis tef* have hindered the country’s use of its own genetic resources.

Patenting of the active ingredients of *Hoodia gordonii* for developing anti-obesity products was done without involving the indigenous San of southern Africa, who had long used the plant to stave off hunger. A benefit-sharing agreement was later agreed with the San.

Carapa guianensis

from use of genetic resources. Access and Benefit-Sharing (ABS) laws established nationally in line with the 2014 Nagoya Protocol are the vehicle for delivering this. The idea is that any benefits arising from commercialisation should be shared with local people who have contributed knowledge about the species through, for example, their traditional use of it (see also Chapter 10).

RECOGNISING LOCAL CONTRIBUTIONS

Some notable cases have arisen where patents have been granted without sufficient consideration of contributed local knowledge. One concerns the crop teff (*Eragrostis tef*). First domesticated in Ethiopia between 4000 and 1000 BCE, teff is used to make *injera,* a flatbread eaten as a staple in the country. In 2003, Dutch company Health and Performance Food International (HPFI) filed a patent with the European Patent Office covering processing of teff flour and related products in the Netherlands. Two years later, it signed an ABS agreement with the Ethiopian Institute of Biodiversity Conservation, and the Ethiopian Agricultural Research Organisation. It was granted the patent in 2007.

The ABS agreement gave HPFI access to teff varieties and the right to use them to make various non-traditional food and drink products. In exchange, HPFI agreed to channel monetary and non-monetary benefits back to Ethiopia. However, when HPFI went bankrupt in 2009 – having only paid EUR 4,000 (approximately USD 4,700) to Ethiopia – it transferred the intellectual property around teff to new companies that were not party to the original agreement. This not only curtailed the return of benefits to Ethiopia, it prevented the nation from using its own teff products and from setting up new ABS agreements in countries covered by the patent.

When the patent owners sued another Dutch company, Bakels, for infringing its intellectual property, the Dutch patent office declared HPFI's initial patents invalid in the Netherlands because they lacked inventiveness; they deemed the process of milling flour and making a dough to be a traditional Ethiopian practice. At present, the patents are still valid in Austria, Belgium, Germany, Italy and the UK, but the ruling presents a good opportunity for Ethiopia to challenge these. The case clearly exemplifies a breakdown in the spirit of the CBD – which should have seen Ethiopian stakeholders engaged from the outset and gaining from the deal – as well as a lack of rigour from patent agents.

"Successful Access and Benefit-Sharing agreements can be achieved only if all parties (genetic resource providers and recipients developing products through patenting) start the process in good faith," says Prof. Sebsebe Demissew of the Department of Plant Biology and Biodiversity Management at Addis Ababa University, and Executive Director of the Gullele Botanic Garden, Addis Ababa, Ethiopia, who was part of the research team. "Both parties are beneficiaries if the process is transparent and the benefits shared with communities."

There are cases where courts have ruled against companies' violation of the rights of traditional communities. An example is that involving the manufacture of soap, made from the murumuru palm tree (*Astrocaryum murumuru*) in Brazil. The Asháninka people, of Acre state in northern Brazil, had long worked in partnership with Asháninka Apiwtxa Association and the Indigenous Research Centre (CPI). They used their traditional knowledge to identify native plant species that might be used in products. However, in 1996, a researcher hired by Asháninka Apiwtxa and CPI started a company, called Tawaya, without consulting or involving the indigenous people, intending to make murumuru soap.

After registering with the Brazilian Health Regulatory Agency in 2004, Tawaya began marketing the soap in 2005. The following year, the Federal Public Ministry in Acre initiated a civil public lawsuit to investigate whether Tawaya had exploited traditional knowledge. In 2019, the Genetic Heritage Management Council ruled in favour of the Asháninka. It considered that Tawaya had made improper use of the traditional knowledge in manufacturing the product without sharing the benefits with the indigenous community. The company was ordered to pay a BRL 5 million fine (just over USD 930,000).

"The ruling will send the message out to companies that if they are going to file a patent to make something like a cosmetic or soap, then they need to show inventiveness, and not just be replicating an existing use of the plant," says Prof. Simmonds. "In this case, the company chose to manufacture the soap in more or less the same way as the local community, not recognising that this was considered 'prior art' and thus not new."

TRANSPARENCY IS KEY

India sets a good example on how to approach patenting of plant and fungal material. Between 1982 and 1988, the Government of India launched a multidisciplinary research project, involving many institutions, called the 'All India Coordinated Research Project on Ethnobiology'. This project documented traditional uses of biodiversity and shared the information, including for patenting decisions. In 2002, the government established an ABS and Patent process. The Indian Biodiversity Act requires companies to obtain prior approval from the National Biodiversity Authority to obtain biological resources for any form of commercial use or patent approval.

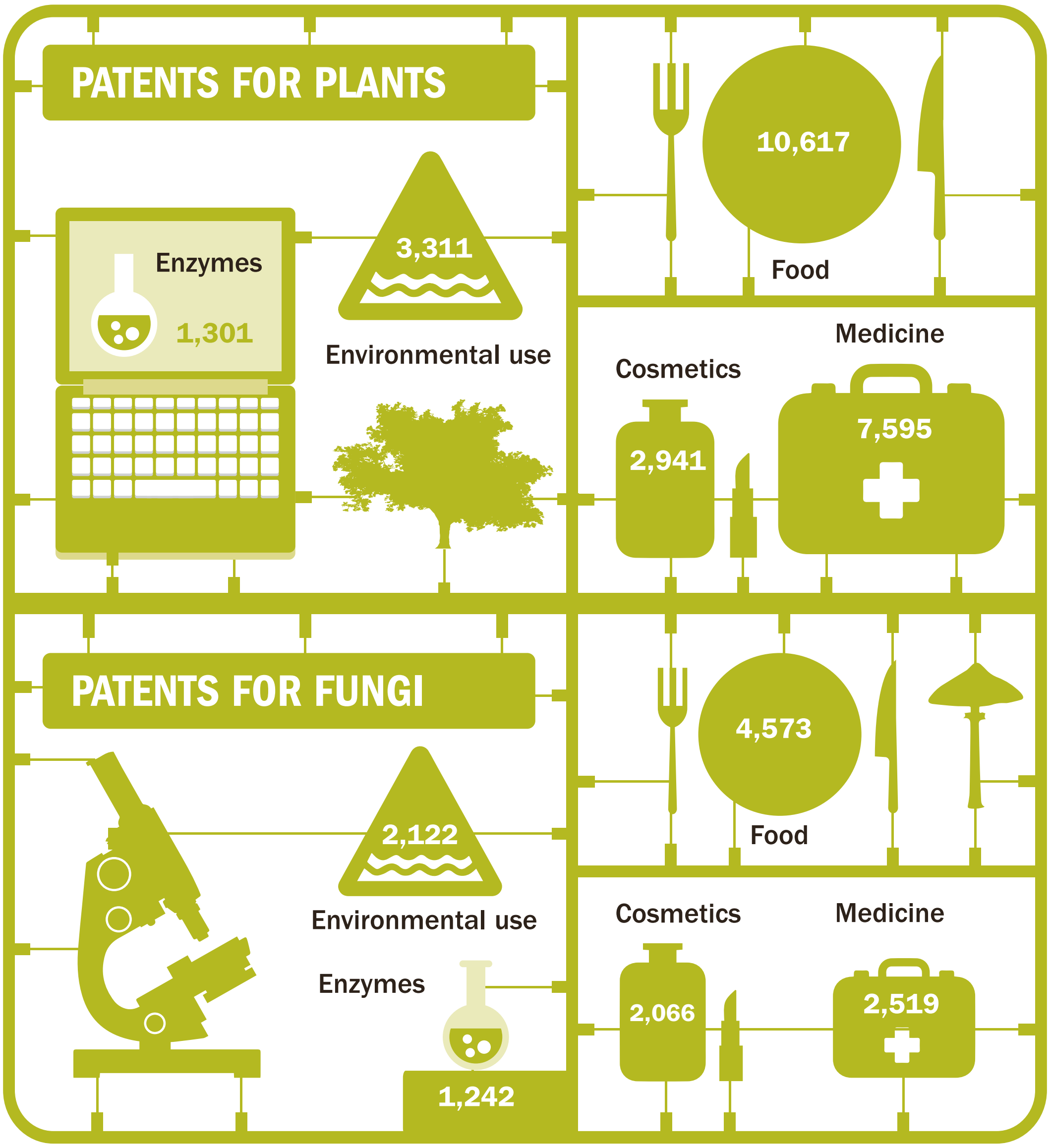
To date, the authority has received more than 3,500 applications and signed over 1,000 ABS agreements, resulting in 2,428 patent applications for inventions, of which 729 have been granted. It aims to encourage patenting of nature-based products while ensuring that benefits generated by the patent holder are shared according to the ABS agreement.

"SUCCESSFUL ACCESS AND BENEFIT-SHARING AGREEMENTS CAN BE ACHIEVED ONLY IF ALL PARTIES (GENETIC RESOURCE PROVIDERS AND RECIPIENTS DEVELOPING PRODUCTS THROUGH PATENTING) START THE PROCESS IN GOOD FAITH"

The patent system has been criticised in recent years for failing to prevent the misappropriation of traditional knowledge, such as methods long used by communities to make foods and medicines.

FIGURE 2: The latest patents for plants and fungi

In the last ten years, the following types of products using plants and fungi have been patented through the European Patent Office.



These benefits are intended to help conserve India's natural resources and support development of local communities. Other countries could emulate this approach, although those with an oral tradition of passing on knowledge might struggle to easily document traditional plant uses.

The Kew-led team searched records of plant-based patents filed in the past decade at the European Patent Office. They identified 25,765 patents for food, medicine, environmental uses, cosmetics and enzymes, while the equivalent search for fungal-related innovations revealed 12,522 patents (see Figure 2). Most applications came from China, South Korea and the USA (and Japan for fungi). The innovations ranged from use of the hinoki cypress tree (*Chamaecyparis obtusa*) to control odours, to the application of a species of white rot fungus, *Phanerochaete sordida,* to degrade neonicotinoid insecticides. Very few applications came from biodiverse countries in Africa or South America, other than South Africa and Brazil, respectively.

OVERCOMING CONCERNS

Some countries and companies remain guarded about patenting nature-based products because of past experiences of 'biopiracy'. Countries are concerned about being exploited, while companies worry that uncertainties over accessing genetic material and sharing benefits leave them vulnerable. The absence of a worldwide patent is also an issue, as paying for many national patents can be prohibitive for small ventures. And some places simply don't have the infrastructure in place to facilitate patenting. "Very few

Among recent patents is one associated with using the hinoki cypress tree (*Chamaecyparis obtusa*) to control odours.

patents are coming from Africa, as there isn't always the infrastructure for filing them," explains Prof. Simmonds.

New technology may lend a hand to make the patenting process for plant and fungal material more straightforward. DNA technology is making it possible to patent traits conveyed in 'nucleic acid sequences' (the genetic code in an organism's DNA). Using this approach, a company could take a trait that enables a plant to store water and use it within a cultivar to make a drought-tolerant crop, for example through gene editing. In such a circumstance, a local community may be owed benefits for highlighting the water-storing capabilities of the plant to the company. However, if the patent covered the insertion of this gene into another species, it would be unlikely that the community would have any claim over the gene-editing aspect of the process.

The commercialisation of products derived from plant and fungal resources via patents has the potential to generate wealth, reduce poverty, improve human well-being and raise awareness of the value of biodiversity, incentivising its conservation. Therefore, a case can be made to increase the diversity of plants and fungi being used in commercial goods. However, this demands better patenting infrastructure in some countries, greater research on the natural resources in biodiverse nations, and stronger international agreements governing access to and sharing of benefits. Fulfilling these goals could bring new foods, medicines and materials to fruition that will support humanity in the millennia to come.

This chapter is based on the following scientific paper published in *Plants, People, Planet*, where you can find more information and references: Simmonds et al. (2020). Biodiversity and patents: Overview of plants and fungi covered by patents. *Plants, People, Planet* 2(5). DOI: https://doi.org/10.1002/ppp3.10144

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Read Chapter 12 to find out how fundamental science underpins work to conserve biodiversity in the UK and its overseas territories.

"IT IS A REAL SHAME THAT MORE PLANT- AND FUNGUS-DERIVED MATERIALS AREN'T SUBJECT TO APPROPRIATE PATENTS, BECAUSE IT WOULD INCREASE THE ECONOMIC VALUE OF BIODIVERSITY"

PLANTS AND FUNGI OF THE UK AND ITS OVERSEAS TERRITORIES

In this chapter, we find out: that botanists disagree on how many flowering plants there are in the UK, and mycologists are finding 50 new fungi there a year; that the UK's overseas territories have many unique plant taxa; why in-depth knowledge about species is critical for conservation; and how ash dieback disease could cost the UK £14.6 billion.

Norman Island in the British Virgin Islands, one of the UK's 14 overseas territories

DESPITE A LONG TRADITION OF BOTANY AND MYCOLOGY IN THE UK, WE STILL DON'T KNOW EXACTLY WHAT PLANTS AND FUNGI GROW THERE, AND ARE ONLY JUST UNCOVERING THE BIODIVERSITY OF ITS OVERSEAS TERRITORIES. FILLING KNOWLEDGE GAPS IS VITAL FOR INFORMING CONSERVATION EFFORTS.

You might think we have little to discover about wild species growing on British soil. The flora of mainland UK is certainly one of the most studied in the world, made easier by its relatively modest size. However, even today there is no single agreed list of the UK's flowering plants. And while the bryophytes (mosses, liverworts and hornworts) and seaweeds are well documented, freshwater algal diversity is little known, and fungi remain enigmatic. When you add plants and fungi inhabiting the UK Overseas Territories (UKOTs; see Figure 1) to the equation, we still have much to learn.

These are the main findings of a review of the status of, and threats to, plant and fungal diversity in Great Britain and the UKOTs. Conducted by Kew and an international team of collaborators, the study examined data on vascular plants and bryophytes, plus freshwater, terrestrial and marine algae. For fungi, the scientists assessed Basidiomycota, Ascomycota (including lichenised fungi), and other groups for which data were available. Geographical coverage was limited to Great Britain, following the *British Red Data Book for Vascular Plants*, with the Channel Islands and Northern Ireland excluded. The Sovereign Base Areas of Akrotiri and Dhekelia were also excluded due to the difficulties of disentangling data from the whole island of Cyprus.

"As we worked on the paper, we realised there are still a lot of unknowns about what information gaps exist," said Prof. Michael Fay, Senior Research Leader in Conservation Genetics at Kew. "We've identified areas that we know quite a lot about, but we've also identified where the gaps are. The real take-home message for me is that there isn't an absolutely standard list of the UK's vascular plant flora. So, if somebody asks, 'How many genera do you have?' or 'How many species do you have?', there isn't one answer – even for the UK."

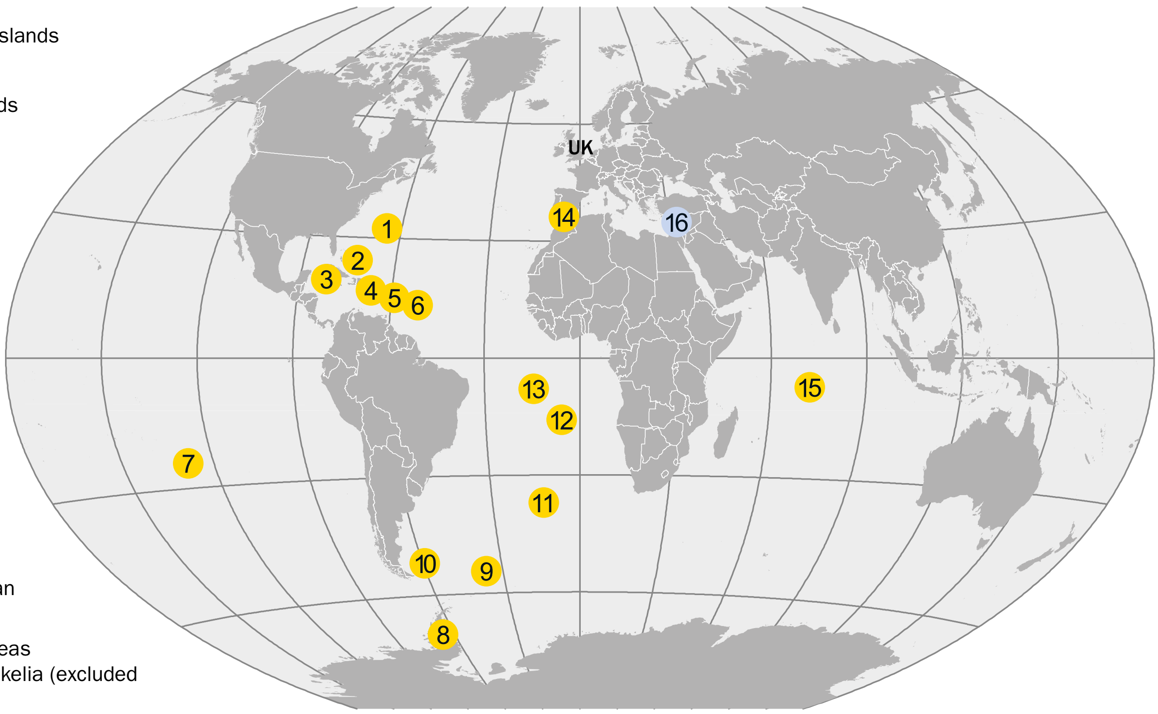
GETTING THE MEASURE OF BRITISH PLANTS AND FUNGI

The Botanical Society of Britain and Ireland (BSBI) database lists 3,025 native vascular plant taxa comprising 2,233 species, 425 subspecies and 367 varieties. There are an additional 5,976 non-native taxa. The BSBI list differs from others mostly because of lack of agreement around the exact number of apomictic taxa – those that reproduce asexually, without fertilisation – in Britain.

FIGURE 1: Location of the UK Overseas Territories (UKOTs)

St Helena, Tristan da Cunha and Ascension Island are treated administratively as a single unit, resulting in a total of 14 UKOTs.

1. Bermuda
2. Turks and Caicos Islands
3. Cayman Islands
4. British Virgin Islands
5. Anguilla
6. Montserrat
7. Pitcairn Islands
8. British Antarctic Territory
9. South Georgia and South Sandwich Islands
10. Falkland Islands
11. Tristan da Cunha
12. St Helena
13. Ascension Island
14. Gibraltar
15. British Indian Ocean Territory
16. Sovereign Base Areas of Akrotiri and Dhekelia (excluded from this review)




UK temperate rainforest is a globally important lichen habitat that occupies just 1% of Earth's land surface.

For example, natural hybridisation and apomixis have led some botanists to recognise more than 400 species of brambles (*Rubus*).

The uncertainty around the status of apomicts is important because if you accept them as species to be counted individually as part of Britain's overall flora, then you also raise the number of endemic taxa – that is, those that do not occur naturally anywhere else – and therefore also the number of rare taxa. This has important implications for conservation.

The 2014 update of the checklist of bryophyte flora of Britain and Ireland (based on data collected by the British Bryological Society) lists 1,069 species (767 mosses, 298 liverworts and four hornworts), along with five subspecies and 33 varieties. One new introduction has since been added, along with 16 species that had previously been overlooked or assessed differently. Seven bryophytes are currently considered endemic to Britain. The 2016 revision of the Natural History Museum's seaweed checklist, meanwhile, includes 644 native taxa (348 red algae, 110 green algae and 186 brown algae), along with 31 non-native species.

The diversity of freshwater algae is less well documented. The 2011 *Freshwater Algal Flora of the British Isles* reports 3,173 taxa (including 14 phyla and 2,480 species), with green algae accounting for 1,588 species and 626 subspecific taxa. The majority of green algae (1,400 taxa) are single-celled, microscopic organisms in the order Desmidiales. There are also 30 stoneworts recognised, but these data need updating. In addition to the species listed above, other authors suggest that 2,800 species of diatoms – algae with cell walls built from silica – also inhabit Britain's freshwater environments.

Estimates for the number of UK fungal species range from 12,000 to 20,000 species, with at least 50 new additions each year. No comprehensive checklist of British fungi exists. There are, however, a few recent or updated checklists for specified groups of fungi in specified geographic areas, for example lichens and Basidiomycota in Britain and Ireland (curated by the British Lichen Society and Kew, respectively); and rusts, smuts and powdery mildews in Wales (authored by the Welsh Rust Group and other specialists). Defining and listing non-native fungi is difficult, because there is usually little evidence to show how the incomers arrived. Some non-native plant pathogens, such as the eastern Asian fungus *Hymenoscyphus fraxineus*, which is responsible for ash die-back disease, are a major challenge (see Box 1, over page).

"Many people associate fungi with the mysterious emergence of mushrooms and toadstools seen in autumn," says Dr Martyn Ainsworth, Research Leader in Mycology at Kew. "But many more fungi lead hidden lives inside plants or soil and may only reveal themselves when their DNA is sequenced and analysed. We need to sequence and, where necessary, re-identify our national fungal reference collections and integrate the results with those rapidly accumulating from environmental sequencing. The resulting DNA-backed national fungal distribution maps would be an innovation as mycologically exciting as the invention of the microscope."

BOX 1: Ash conservation in action

The European ash (*Fraxinus excelsior*) is native to the UK and mainland Europe. In Britain, it is the second most abundant tree species in small woodland patches and the third most abundant in larger areas of forest. As many as 125 million trees exist in UK woodlands, with a further 27–60 million growing in hedgerows, along roads and railways, and within towns and cities.

More than 1,000 species are associated with ash: 12 birds, 55 mammals; 239 invertebrates; 78 vascular plants; 58 bryophytes; 548 lichens; and 68 non-lichenised fungi. Of these, 45 are believed to have only ever been found on ash. The UK government's Department for Environment, Food and Rural Affairs estimates the social and environmental benefits of ash woodlands in Great Britain to be worth more than £230 million a year (USD 295 million). However, the species is threatened by ash dieback disease, caused by the eastern Asian *Hymenoscyphus fraxineus* fungus, which is now present throughout Europe.

Recent analysis of data across Europe shows ash mortality rates differ depending on woodland type. The total cost of the disease to the UK, encompassing felling dead trees, replanting new ones and the loss of ecosystem services, has been estimated at £14.6 billion (USD 19 billion). Following a screening trial for tolerant trees, 3,000 saplings have been planted as the basis of a future breeding programme.

INVESTIGATING THE UKOTS' BIODIVERSITY

The UKOTs – 14 former British colonies that have elected to remain under British sovereignty – comprise islands and peninsulas throughout the world's oceans. Together, they cover an area seven times the size of the UK. Although they host a rich flora and mycota, there has been no systematic analysis of the status of UKOT plant and fungal diversity because no centralised data resource exists to facilitate it.

From online databases, including Plants of the World Online, the review team estimates the current known flora of the UKOTs to be 4,093 vascular plant taxa (including species, subspecies and varieties). While native status is not always known, on average 60% of taxa are considered native, ranging from 88% for the Turks and Caicos Islands down to 21% for St Helena and 18% for Ascension Island, which have both been highly affected by introduced species. The UKOTs have 191 endemic plants, and a further 17 are recorded as extinct. Three territories, Tristan da Cunha, St Helena and the Cayman Islands, account for 64% of this endemism. New species sometimes emerge; the cliff hair grass (*Eragrostis episcopulus*) was first described from St Helena in 2012, and the Falkland nassauvia *(Nassauvia falklandica)* from the Falkland Islands in 2013.

Far less is known about non-vascular plants in the UKOTs. There are records of 110 species for St Helena, of which 26 are endemic; the island is considered a centre of endemism for bryophytes. For Ascension Island, 87 species (60 mosses, 23 liverworts, four hornworts) have been recorded, including 12 endemics and four near endemics. And while the Falkland Islands' online portal for liverworts and hornworts reports 146 taxa, data are thin on the ground for other territories. Meanwhile, information on seaweeds is sparse across the UKOTs, with new species regularly reported.

"In recent years, we have made considerable progress in our knowledge of the status of UK seaweeds, although we are only just beginning to understand the scale of seaweed diversity for the UK's overseas territories," says Prof. Juliet Brodie, Merit Researcher at the Natural History Museum, London, who was part of the Kew-led review team. "For example, our recent work on the Falklands Islands' seaweed flora revealed that more than 25% of species were undescribed and that there is a wealth of diversity yet to be catalogued." The review team was unable to summarise UKOTs fungi because of lack of data.

SIGNIFICANT HABITATS

The richness of vascular plants is relatively low in both Britain and the UKOTs, although some overseas territories have many endemic species. Phylogenetic diversity – the evolutionary history represented within a group of organisms – is also likely to be low, although this has not been rigorously tested. Nonetheless, there are some wild plant and fungal assemblages and habitats of international significance. Many of these have been recognised and protected under UK legislation, and further areas have been defined as Important Plant Areas (IPAs) and Important Fungus Areas, a programme developed by PlantLife International.

Only two of the UKOTs have completed IPA assessments. This work has identified 17 IPAs in the Falkland Islands and 18 Tropical IPAs, or TIPAs, in the British Virgin Islands (BVI). The BVI are home to globally and nationally threatened plants, as well as nationally threatened habitats. "Having accurately mapped distributions of threatened species and habitats included in the national GIS [Geographic Information System] helps enormously with planning decisions," says Nancy Woodfield-Pascoe, Deputy Director for Science at the National Parks Trust of the Virgin Islands, who was also part of the review team. "We are actively involved in advising the BVI Government on the biodiversity importance of sites during the development planning process."

The other UKOTs have delineated various protected areas and reserves. For example, St Helena's unique cloud forest is protected as the Peaks National Park; Ascension Island's remaining cloud forest is conserved in Green Mountain National Park; and Montserrat's key biodiversity, threatened by eruptions from the Soufrière Hills volcano, is conserved in the Centre Hills Reserve.

CONSERVATION STATUS AND THREATS TO UK SPECIES

Understanding what biodiversity exists and where it occurs is critical for conservation. This is because decisions around priorities for conservation are based primarily on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. Until species are named and their conservation status assessed, they cannot feature in conservation initiatives.

For Britain, the online Red List maintained by the GB Red List Group on the BSBI's website lists 152 vascular plant taxa as Critically Endangered or Endangered according to IUCN Red List criteria. This includes some species of whitebeam (*Sorbus*) and lady's mantle (*Alchemilla*), which are mostly apomictic, along with some other critical taxa, primarily eyebrights (*Euphrasia*), which hybridise widely. It does not include apomictic brambles or dandelions (*Taraxacum*). There is also a published Red List for Great Britain, and separate Red Lists for England and Wales.

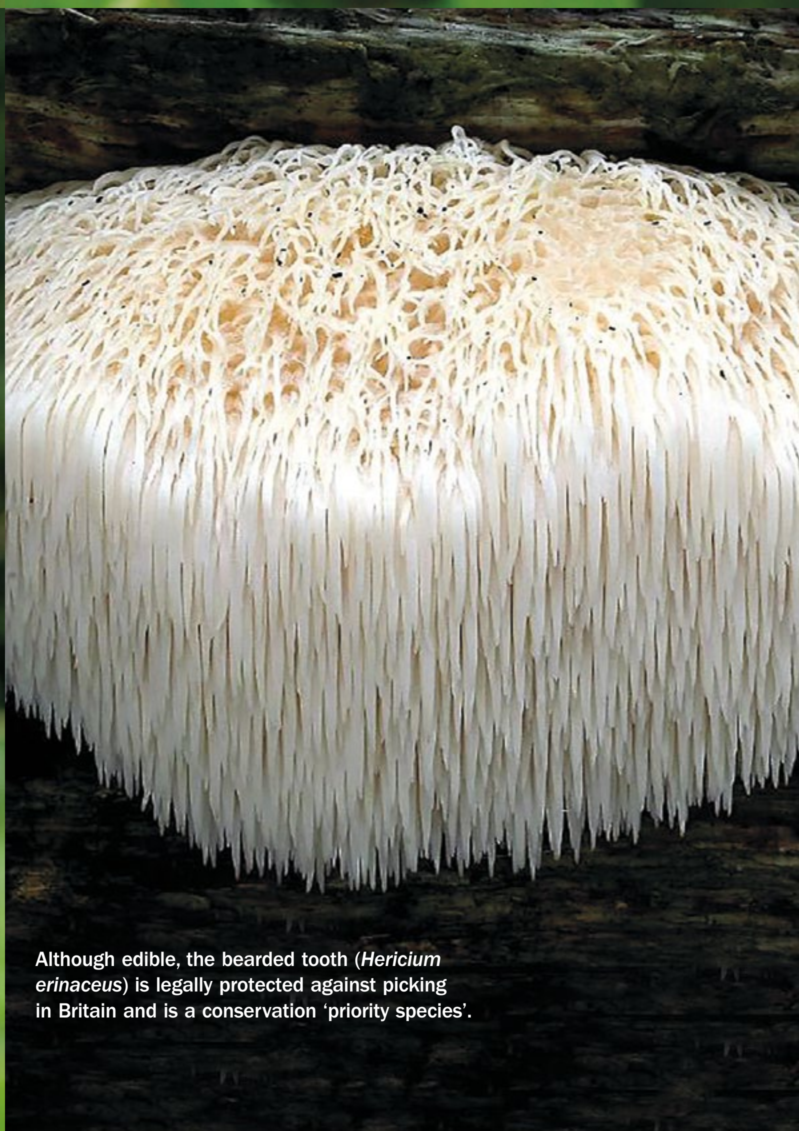
Regarding non-vascular plants, more than 20% of Britain's liverworts and more than 25% of its mosses are in an IUCN threat category, so at risk of extinction. Around 13.5% of British bryophytes are also threatened at European level, and many species at the global level. A provisional Red List for UK seaweeds, meanwhile, cites a third as 'Data Deficient', indicating that we know too little about their distribution to assess their conservation status.

ESTIMATES FOR THE NUMBER OF UK FUNGAL SPECIES RANGE FROM 12,000 TO 20,000 SPECIES, WITH AT LEAST 50 NEW ADDITIONS EACH YEAR

A landslide wiped out the only known wild specimen of Pitcairn Island's yellow fatu (*Abutilon pitcairnense*) in 2005. Fortunately, cuttings had already been taken and plants are in *ex situ* cultivation.

The Cayman sage (*Salvia caymanensis*) was considered extinct from the mid-1960s but re-emerged from an unknown soil seed bank on ground disturbed during roadworks in 2007.

Red helleborine (*Cephalanthera rubra*) is one of the rarest orchids in the UK, currently known from only two populations in southern England.



Although edible, the bearded tooth (*Hericium erinaceus*) is legally protected against picking in Britain and is a conservation 'priority species'.

They are, however, threatened by habitat loss, harvesting, non-native species and climate change.

Distribution and status data are likewise lacking for most freshwater algae, but we know that the rivers, streams and ponds they inhabit are largely degraded. Stoneworts (Charales) are among the most severely threatened plants in Britain. Living in fresh and brackish water, where they provide food and habitats for fish, they are very sensitive to water quality. Of the 30 known species, 17 are nationally rare or extinct. Nitrate and phosphate run-off from urban areas and farming is particularly detrimental to them, as they struggle to compete with nutrient-loving algae.

Forty-five British species of fungi (out of 280 on the global Red List) are globally threatened or near threatened. The fact that most inhabit nutrient-poor, grazed grasslands identifies this habitat as particularly vulnerable. However, as mycologists assess more fungi, more at-risk fungal habitats will likely emerge. UK temperate rainforest is a globally important lichen habitat that occupies just 1% of Earth's land surface. Overall, the threats facing fungi in the UK are habitat loss, climate change – particularly alternating droughts and deluges – and nitrification. However, only one family of British fungi has an officially approved Red List, highlighting a significant knowledge gap.

"Many threatened British species are covered by conservation programmes, being, for example, listed on Section 41 of the Natural Environment and Rural Communities (NERC) Act [which lists species and habitats considered to be of principal importance for conserving biodiversity in England] or Schedule 8 of the Wildlife and Countryside Act [which lists plants and fungi requiring protection from destruction, picking or trade]," explains review co-author Ian Taylor, Senior Specialist (vascular plants) for Natural England, which is the UK government's adviser for the natural environment in England. "Section 41 has enabled Natural England to focus conservation action on those species objectively assessed as being most in need of it – it's helped level-up the playing field across the taxonomic spectrum and given due prominence to plants and fungi."

INCOMPLETE KNOWLEDGE OF THE UKOTS' THREATENED BIODIVERSITY

A global Red List for UKOTs is far from completion, although many territories are undertaking Red-Listing assessments with a focus on rare and endemic taxa. Currently, 515 taxa have been globally assessed: around 21% of the total. Of these, 135 are in a threatened category, with 52 Critically Endangered, 47 Endangered and 36 Vulnerable taxa. The top four threats to these taxa are developments related to tourism and recreation, invasive species, the expansion of urban areas, and agriculture. National Red Lists have been completed for the Falkland Islands and Cayman Islands, and are in progress in several other territories. Bermuda has been testing new approaches to accelerating the Red-Listing process (see also Chapter 2).

The conservation status of UKOT fungi represents another major knowledge gap. More than half of lichen species on St Helena are categorised as rare, and five are thought to be extinct on the island. However, only St Helena's endemic foliose lichen *Xanthoparmelia beccae* is on the global Red List, where it is listed as Vulnerable. A smut fungus from the Falkland Islands, *Anthracoidea ortegae*, is also listed as Vulnerable.

"Unless species are included on the global Red List, people can't point to politicians to say, 'this is a globally important species'," says Dr Colin Clubbe, Head of Conservation Science at Kew. "If there is a new hotel or a cruise-ship dock being planned in one of the Caribbean UKOTs, it is invaluable to be able to say 'in this area, we have six globally threatened species, representing 50% or more of their global populations'. This provides the evidence for our partners to push for conservation action."

GUIDING FUTURE CONSERVATION EFFORTS

Habitat loss and fragmentation, out-of-control introduced species, pollution, exploitation and climate change are having a significant effect on Earth's natural environments. Recent studies indicate that 75% of terrestrial lands worldwide have experienced some type of land-use change. And, in 2020, the World Economic Forum ranked biodiversity loss as the third highest risk to the global economy.

Conservation efforts, including the incorporation of endemic and threatened species into living collections and seed banks, and the designation of protected areas, are contributing to preventing biodiversity loss. The Millennium Seed Bank Partnership, led by Kew, has catalysed seed conservation activities globally, and 72% of the UK's seed-bearing plants are banked at species level. UKOTs are at varying stages of seed conservation: seeds from the native floras of all of South Georgia, 81% of the Falkland Islands, 43% of Turks and Caicos Islands, and 41% of St Helena are banked at the Millennium Seed Bank. In addition, many species are being cultivated in native plant nurseries in-territory.

Setting conservation priorities requires detailed knowledge of biodiversity and threats. Targeting the knowledge gaps outlined here, the greatest of which are for fungi, can help inform conservation decisions for Britain and the UKOTs. Action is urgently needed to prevent species from going extinct and secure the future of these vital natural assets.

This chapter is based on the following scientific paper published in *Plants, People, Planet*, where you can find more information and references: Clubbe et al. (2020). Current knowledge, status and future for plant and fungal diversity in Great Britain and the UK Overseas Territories. *Plants, People, Planet* 2(5). DOI: https://doi.org/10.1002/ppp3.10142

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Acknowledgements

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Citation

This report should be cited as:

Antonelli, A.*, Fry, C.*, Smith, R.J.*, Simmonds, M.S.J.*, Kersey, P.J.*, Pritchard, H.W.*, Abbo, M.S., Acedo, C., Adams, J., Ainsworth, A.M., Allkin, B., Annecke, W., Bachman, S.P., Bacon, K., Bárrios, S., Barstow, C., Battison, A., Bell, E., Bensusan, K., Bidartondo, M.I., Blackhall-Miles, R.J., Borrell, J.S., Brearley, F.Q., Breman, E., Brewer, R.F.A., Brodie, J., Cámara-Leret, R., Campostrini Forzza, R., Cannon, P., Carine, M., Carretero, J., Cavagnaro, T.R., Cazar, M.-E., Chapman, T., Cheek, M., Clubbe, C., Cockel, C., Collemare, J., Cooper, A., Copeland, A.I., Corcoran, M., Couch, C., Cowell, C., Crous, P., da Silva, M., Dalle, G., Das, D., David, J.C., Davies, L., Davies, N., De Canha, M.N., de Lirio, E.J., Demissew, S., Diazgranados, M., Dickie, J., Dines, T., Douglas, B., Dröge, G., Dulloo, M.E., Fang, R., Farlow, A., Farrar, K., Fay, M.F., Felix, J., Forest, F., Forrest, L.L., Fulcher, T., Gafforov, Y., Gardiner, L.M., Gâteblé, G., Gaya, E., Geslin, B., Gonçalves, S.C., Gore, C.J.N., Govaerts, R., Gowda, B., Grace, O.M., Grall, A., Haelewaters, D., Halley, J.M., Hamilton, M.A., Hazra, A., Heller, T., Hollingsworth, P.M., Holstein, N., Howes, M.-J.R., Hughes, M., Hunter, D., Hutchinson, N., Hyde, K., Iganci, J., Jones, M., Kelly, L.J., Kirk, P., Koch, H., Krisai-Greilhuber, I., Lall, N., Langat, M.K., Leaman, D.J., Leão, T.C., Lee, M.A., Leitch, I.J., Leon, C., Lettice, E., Lewis, G.P., Li, L., Lindon, H., Liu, J.S., Liu, U., Llewellyn, T., Looney, B., Lovett, J.C., Łuczaj, Ł., Lulekal, E., Maggassouba, S., Malécot, V., Martin, C., Masera, O.R., Mattana, E., Maxted, N., Mba, C., McGinn, K.J., Metheringham, C., Miles, S., Miller, J., Milliken, W., Moat, J., Moore, P.G.P., Morim, M.P., Mueller, G.M., Muminjanov, H., Negrão, R., Nic Lughadha, E., Nicolson, N., Niskanen, T., Nono Womdim, R., Noorani, A., Obreza, M., O'Donnell, K., O'Hanlon, R., Onana, J.-M., Ondo, I., Padulosi, S., Paton, A., Pearce, T., Pérez Escobar, O.A., Pieroni, A., Pironon, S., Prescott, T.A.K., Qi, Y.D., Qin, H., Quave, C.L., Rajaovelona, L., Razanajatovo, H., Reich, P.B., Rianawati, E., Rich, T.C.G., Richards, S.L., Rivers, M.C., Ross, A., Rumsey, F., Ryan, M., Ryan, P., Sagala, S., Sanchez, M.D., Sharrock, S., Shrestha, K.K., Sim, J., Sirakaya, A., Sjöman, H., Smidt, E.C., Smith, D., Smith, P., Smith, S.R., Sofo, A., Spence, N., Stanworth, A., Stara, K., Stevenson, P.C., Stroh, P., Suz, L.M., Tambam, B.B., Tatsis, E.C., Taylor, I., Thiers, B., Thormann, I., Trivedi, C., Twilley, D., Twyford, A.D., Ulian, T., Utteridge, T., Vaglica, V., Vásquez-Londoño, C., Victor, J., Viruel, J., Walker, B.E., Walker, K., Walsh, A., Way, M., Wilbraham, J., Wilkin, P., Wilkinson, T., Williams, C., Winterton, D., Wong, K.M., Woodfield-Pascoe, N., Woodman, J., Wyatt, L., Wynberg, R., Zhang, B.G. (2020). *State of the World's Plants and Fungi 2020*. Royal Botanic Gardens, Kew. DOI: https://doi.org/10.34885/172

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The views expressed in this report do not necessarily reflect the views or policies of the authors' organisations or funders.

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Academic publication partners: *Plants, People, Planet*
This report is accompanied by a special issue of expert-reviewed scientific publications in the New Phytologist Foundation's journal *Plants, People, Planet*. The chapters in this report are based on the open access articles in this special issue, entitled *Protecting and Sustainably Using the World's Plants and Fungi*. Further information, data and references for the material presented here can be found at: https://nph.onlinelibrary.wiley.com/toc/25722611/2020/2/5

DOI: https://doi.org/10.34885/172

Printed on 100% recycled paper

The staff and trustees of the Royal Botanic Gardens, Kew and the Kew Foundation would like to thank the Sfumato Foundation for generously funding the State of the World's Plants and Fungi project.

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