Royal Botanic Gardens Kew

Unlocking why plants and fungi matter

Impacts from Kew Science 2012–2018


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Culture

Foreword

Kew's scientific vision is to document and understand global plant and fungal diversity and its uses, bringing authoritative expertise to bear on the critical challenges facing humanity today.

In this booklet we seek to illustrate, through selected examples, how a combination of Kew's extensive collections, databases, scientific expertise and global partnerships have enabled us to make an invaluable and relevant contribution to research, conservation and training in plant and fungal science, addressing some of the biggest challenges facing the global population.

We hope to illustrate something of the breadth and coverage of Kew Science ranging from the climate resilience of Arabica coffee to the role of ectomycorrhizal fungi in Europe's forests; from the conservation impacts of the Millennium Seed Bank Partnership to taxonomy training to tackle critical skills shortages.

This is a companion publication to the report of the independent Review Panel commissioned by Board of Trustees of the Royal Botanic Gardens, Kew. The review advises on the scientific quality and impact of Kew's output over the last five years and assesses Kew's progress to date in achieving the ambitions and targets outlined in the Kew Science Strategy 2015–2020.

We hope you enjoy reading these selected examples and recognise the core purpose of our science stems from a simple but often overlooked truth – all our lives depend on plants and fungi.

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Director of Science

Contents

Introduction

The 20 case-studies in this booklet are just a few examples of Kew's scientific research and the impact it has outside purely academic circles.

Much of Kew's scientific work, and the collections and data we share with our global partners and collaborators, goes to enhance our understanding of plant and fungal diversity. Yet, it is the use of this knowledge to restore and protect natural habitats, contribute to food security and improve the livelihoods of local communities that really demonstrates the importance of Kew's scientific research.

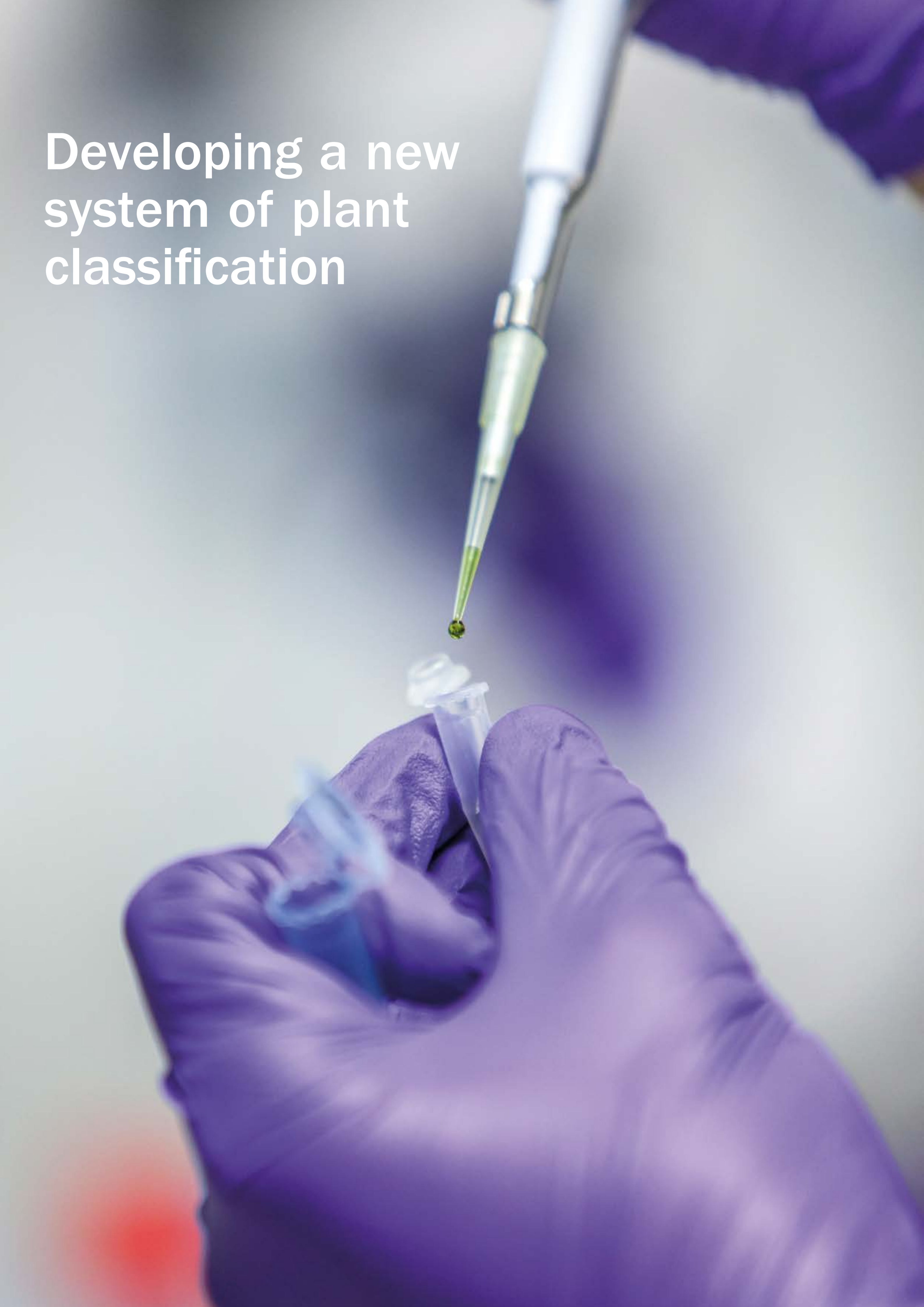
At Kew, over 350 science-based staff are working with partners in more than 100 countries, most of which are in the Global South and who face huge challenges in understanding, preserving and utilising biodiversity. Kew works with these partners, as well as policymakers, commercial organisations and governments, to disseminate the knowledge and expertise it has built up for the past 260 years.

To help frame the importance of our research further, Kew has aligned its research, where appropriate, to the UN's Sustainable Development Goals. Whether it is working towards ending hunger through raising food security and improving nutrition or contributing to the protection, restoration and sustainable use of terrestrial ecosystems, Kew's ability to contribute to the success of these global goals is based on being a unique plant and fungal knowledge resource that the world can draw on.

This document is split into five sections, each of which illustrates an area where Kew scientists, and the work they have done, has led to a demonstrable impact across the world. We hope you recognise the importance of Kew's work, and seek out ways to support its continued success.

Understanding plant and fungal diversity

Developing a new system of plant classification



Summary

Ever since the dawn of the molecular age, Kew has played a leading role in DNA-based research to construct 'family trees' for plants. We have made startling discoveries about the relationships among plants and about their origins – a branch of science known as plant phylogenetics. Since 1998, with the publication of the Angiosperm Phylogeny Group (APG) classification, science has had a radical research tool to understand angiosperms (flowering plants) and their evolutionary history. Since then, in collaboration with other scientists, we have regularly revised the APG system. The latest version, published in 2016, is now widely adopted by scientists worldwide as an essential framework for both pure research and many diverse areas of applied research.

For the efficient study or use of the hundreds of thousands of flowering plant species available, there needs to be a system for ordering them. The 'father of modern taxonomy' Carl Linnaeus had a go in his book *Species Plantarum* (1753), by classifying flowering plants using the male and female parts of flowers. He realised, even then, that this was an artificial system with many unrelated plants grouped together. Two centuries later, there were many alternative classifications based around the appearance of plants but little agreement on which characteristics to use.

The breakthrough came in the 1990s when technological improvements in DNA sequencing led to the APG classification. After the fourth revision, published in 2016, the APG system is now almost unanimously adopted in academic circles worldwide. This is because it reflects a natural classification based on the evolutionary history of plants.

Impact of APG

The influence of APG extends far beyond academia into applied research and education. It can even be seen by the public in rearranged plant beds in botanical gardens and popular books on plants. APG not only classifies plants into groups with far fewer discrepancies than in the past but also shines a light on the evolutionary history of flowering plants.

Education

The next generation of plant scientists are acquainted with the APG classification early in their training, because it is now found in undergraduate textbooks, such as the classic *The Biology of Plants* by Peter H. Raven and colleagues (now in its 8th edition). Meanwhile the general public can find several popular books that refer to, explain, and use the APG system: *The Plants of the World: An Illustrated Encyclopedia of Vascular Plant Families* by M. Christenhusz, M. F. Fay and M. W. Chase (Kew Publishing 2018), which is largely based on Kew's phylogenetic research; and *New Flora of the British Isle*s by C. A. Stace, the most authoritative work for the identification of plants of the British Isles.

Botanic gardens

The APG system and phylogenetics are increasingly the basis of living collections displayed within botanic gardens. For example, our Agius Evolution Garden at Kew opened in May 2019. Other botanic gardens, such as the University of Oxford, University of Cambridge and University of Bristol also have an APG-arranged phylogenetic section. Other reference collections, such as herbaria, are being reorganised to the APG system, these include those at Kew, University of Oxford, University of Cambridge and Leiden University.

Conservation science

The International Union for the Conservation of Nature (IUCN) has adopted the APG system, and phylogenetic information has also been used to inform conservation planning and species prioritisation.

Developing new crops, drugs and foods

Knowing the relationships between crop species and their wild relatives gives plant breeders a head start in developing new crops. Yams (*Dioscorea*) and coffee are two crops where phylogenetics is helping with breeding and conservation. Likewise, the development of new foods and pharmaceutical products in industry is routinely informed by understanding phylogenetics. Several of our industry partners (Procter & Gamble, Boots and Unilever) have agreements that specifically mention the importance of the underlying phylogenetic knowledge. A spin-off from our *Plant and Fungal Trees of Life* project (PAFTOL) is a toolkit of 353 genes that can be used when researching the phylogenetics of flowering plants – this has been marketed as a commercial product.

Background to the research

Traditionally, the classification of angiosperms (flowering plants) was mostly based on morphological, anatomical and biochemical information. In other words, plants were classified by their shape, structure and what they contained. Alternative interpretations of this evidence led to competing classification systems, which were variously followed by different institutions and individuals.

The development of DNA sequencing technologies provided new information that revolutionised both evolutionary studies and our understanding of phylogenetic relationships, and eventually provided the basis for DNA-based classifications. In 1993, one of the most influential and ground-breaking studies on plant classification was published by Kew-based Professor Mark W. Chase. This phylogenetic analysis of angiosperms produced many unexpected results and, together with subsequent works, served as the basis for the first instalment of the Angiosperm Phylogeny Group (APG) classification published in 1998. Subsequent versions of the classification were published, each refining the previous one based on research published in the intervening time; the last revision was in 2016. The APG system is largely seen as the single most authoritative classification of flowering plants.

As part of our 2015–2020 Science Strategy, we have embarked on a large phylogenomic endeavour, the Plant and Fungal Trees of Life project (PAFTOL), which aims to produce genomic-scale data for at least one species of each genera of plants (about 14,000 genera) and fungi (about 8,000 genera). To achieve this, we are using an approach that targets specific regions of the genome across all angiosperms. More than 25% of all genera of angiosperms have been sequenced using this method and the first phylogenetic trees have been reconstructed. The set of probes that was designed for this work is now commercially available and has already been widely used.

What next?

While the 2016 version of APG will not be the final version, the decreasing number of changes means that reorganising collections to reflect changes is becoming less arduous. The resulting system allows greater predictability than previous classifications because the groups that are recognised reflect the evolutionary relationships of flowering plants.

At-a-glance

- **Collaboration**
  In the early 1990s, the first large analyses of flowering plants based on DNA sequences were published. This was the first major group on which large numbers of scientists collaborated, collecting sequences for the same genes, so that the data could be combined.

- **1993 landmark**
  An analysis of 499 species of seed plants was published by Mark Chase and 41 co-authors. This paper was based on sequences of one of the major genes involved in photosynthesis.

- **Re-thinking family trees**
  The results were a mix of the expected and the unexpected. The monocots (such as grasses) still appeared as a group, for example, but the dicots (such as legumes) did not. Some families that had never previously been thought to be related appeared close to each other. One example placed the sacred lotus (*Nelumbo*) close to plane trees (*Platanus*) and banksias (*Proteaceae*).

- **APG system**
  Over the next few years, equivalent data sets for other DNA regions were collected. All told a very similar story. A classification based largely on DNA sequences was published in 1998 as the Angiosperm Phylogeny Group classification or APG for short.

The APG system is largely seen as the single most authoritative classification of flowering plants.

References to the research

This summary was based on an impact paper ‘Utilising insights from the breadth of Kew’s phylogenetic research to generate impact beyond academia – from the Angiosperm Phylogeny Group (APG) to PAFTOL’.

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Acknowledgements

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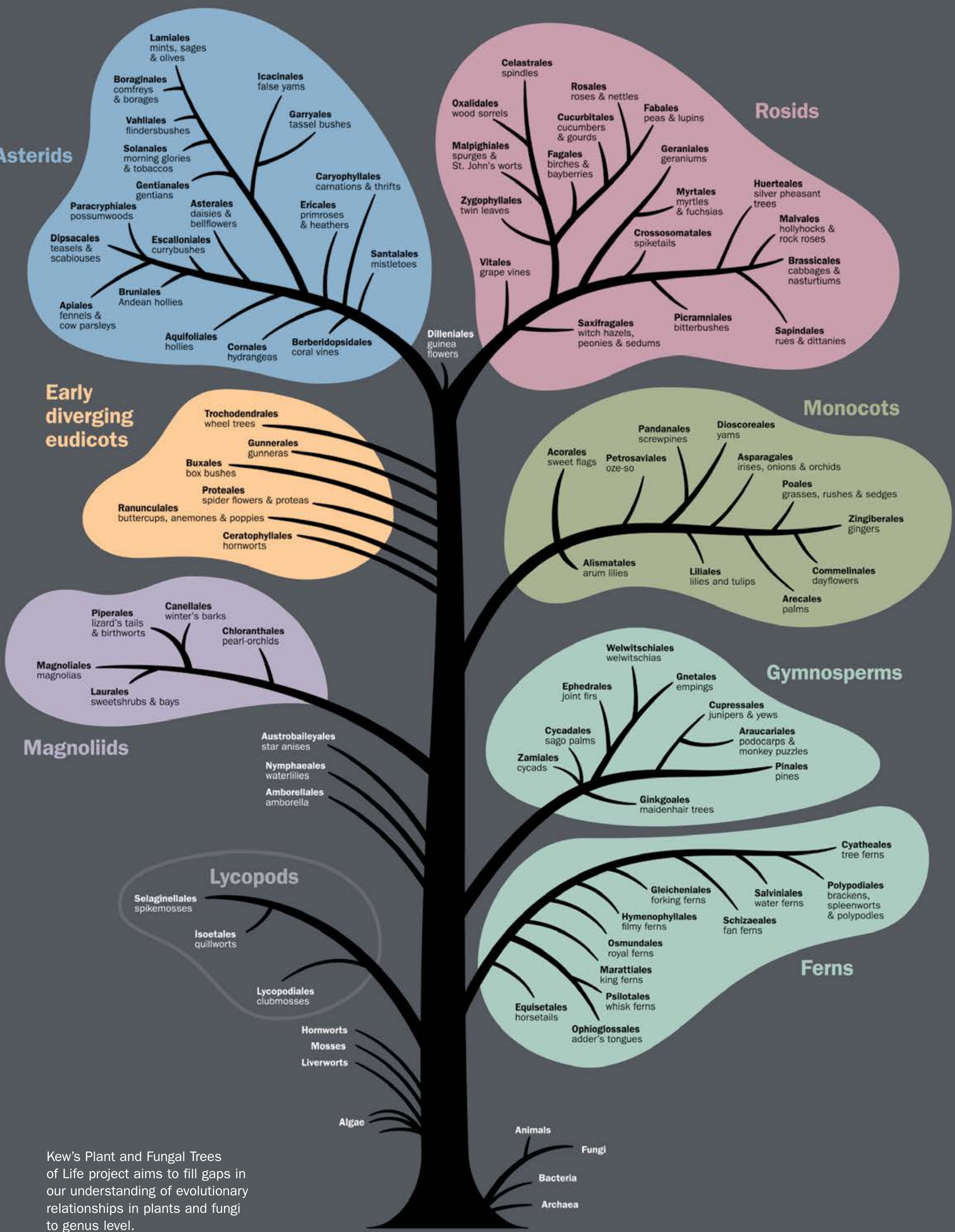
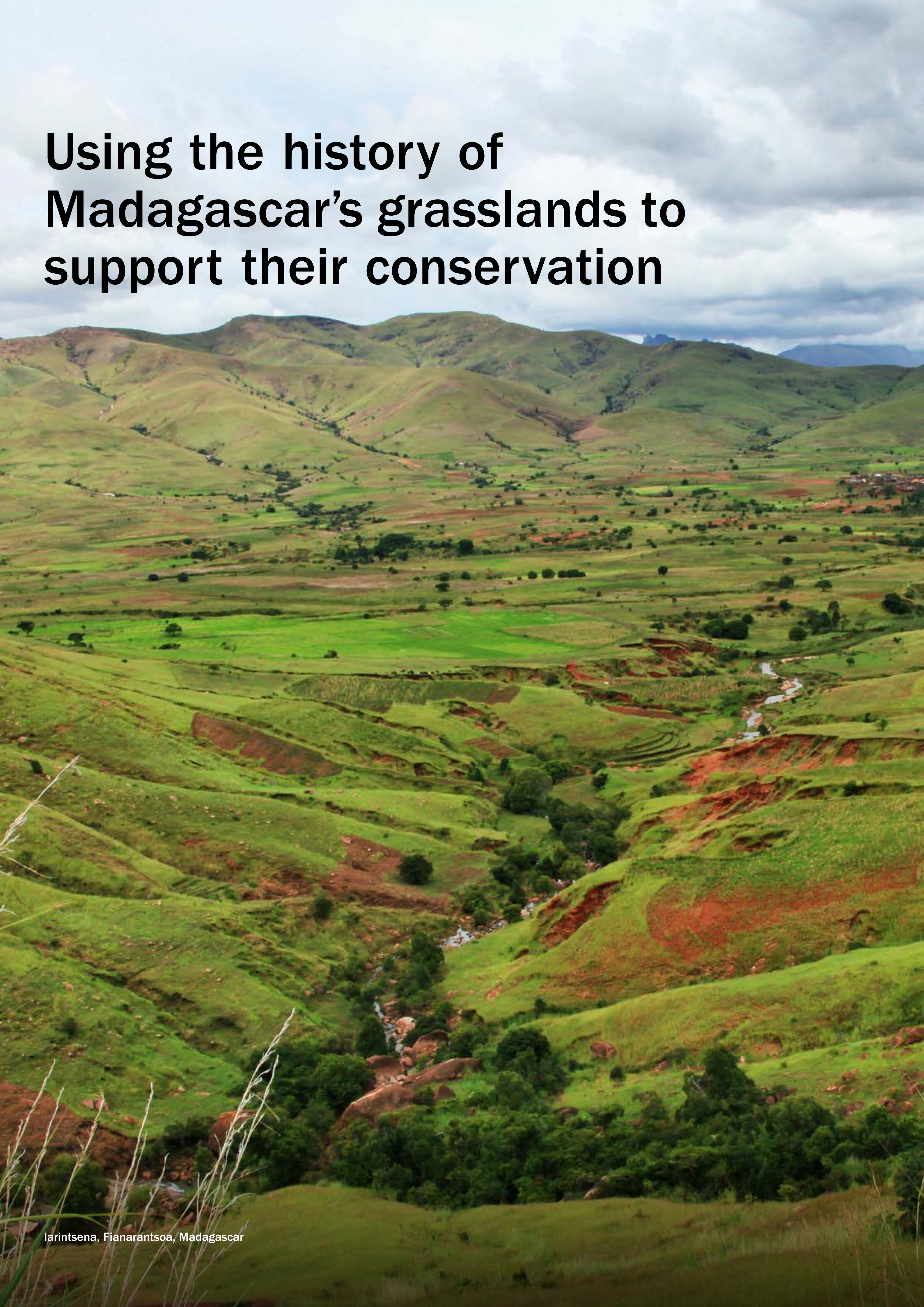


Kew's Plant and Fungal Trees of Life project aims to fill gaps in our understanding of evolutionary relationships in plants and fungi to genus level.

Using the history of Madagascar's grasslands to support their conservation



Iarintsena, Fianarantsoa, Madagascar

Summary

Madagascar's grasses are naturally diverse and many are endemic. There is a growing awareness that many of the open canopy ecosystems in the central highlands are natural in origin, and of the possibility that natural fires can be an ancient feature of ecosystems. Long-term work by Kew's Madagascar team has resulted in legal protected area status for Itremo (a highland limestone plateau dominated by savanna), as well as a long-term management plan and an improved fire-management regime for the region. Fire management in the Ibity Protected Area has been altered so that a larger area is burned in the early dry season, thereby protecting nearby forest from the increased risk of burning later in the dry season.

The dominant narrative since the nineteenth century has stated that pre-human Madagascar was forested and that people destroyed the forest by burning, leading to degraded anthropic landscapes of non-native grasses. Our Madagascar Poaceae research programme is achieving a paradigm shift in this narrative. Eight years of multidisciplinary research led by Maria Vorontsova in Madagascar, with a focus on the central highlands, has documented native grasses and suggested natural origins for open canopy ecosystems.

Impact of the research

Increasing awareness of grass diversity

From 2012 to 2019, Maria Vorontsova ran training courses and workshops related to grass diversity and identification. Since February 2018, 150 copies of the *Identification Guide to Grasses and Bamboos in Madagascar* (Vorontsova et al., 2018) have been distributed to Malagasy professionals free of charge. In a collaboration from 2012 to 2014, Maria Vorontsova and Michelle Cleave, a Kew horticulturist, established the Grass Garden in Parc Tsimbazaza, Antananarivo.

Identifying and managing alien invasive grasses

Until we started our research, no complete list of Madagascar grasses had ever been attempted and the country did not have any system for recording or monitoring invasive plants. A 2019 draft National Strategy for Native and Alien Grasses of Madagascar now aims to establish a monitoring strategy for any potentially economically damaging arrivals.

Ecosystem origin and debate

The possibility of a natural origin for grassy ecosystems and the acceptance of fires, which are currently illegal, remains a controversial subject in Madagascar. Future consequences of the outcome of this debate are significant indeed. The new government of Madagascar, formed in January 2019, is in the process of implementing a country-wide tree-planting programme that is expected to include the planting of eucalyptus trees in grassland areas. Similar initiatives in South Africa and South America have shown that planting eucalyptus in natural grasslands reduces downstream water supply (critical for Madagascar's rural economy which is dependent on rice paddies) and dries out deeper soil, sometimes reducing soil carbon storage. Future awareness of natural grasslands could prevent the planting of eucalyptus trees in these areas.

Changes to protected area management

The Itremo Protected Area (24,788 ha) is a unique highland limestone plateau dominated by savanna now under formal management by Kew. This legal protection is very significant for our work in Madagascar. Regular fires have always been part of the Itremo and Ibity ecosystems, even though management regimes prohibit them in an attempt to prevent the destruction of nearby forests.

Maria Vorontsova and Caroline Lehmann (who previously worked on fire management at the Kakadu National Park, Australia) have engaged with area managers to look at the possibility that controlled fires in the afternoons of the early dry season could clear grass biomass accumulation, thus protecting the forests from hotter fires. Since 2018, trial burning plots have been used in Itremo to demonstrate the impact of fire, a project that is supported by the Critical Ecosystem Partnership Fund. A controlled fire regime (managed by the Missouri Botanical Gardens Madagascar team) has now been implemented at the Ibity Massif. Eucalyptus and pine trees raise the temperatures of grass fires, so a programme to eradicate pines in Itremo has been active since 2016.

Background to the research

From 2010 to 2019, the diversity of Madagascar's Poaceae was assessed by Maria Vorontsova, with support from Kew's Madagascar team and others. This established an estimated 541 species of Poaceae in Madagascar, about 40% of these endemic: an unusually high level of endemicity for grasses.

Phylogenetic analyses demonstrated that grass lineages colonised Madagascar during the global Miocene grassland expansion, which included at least 44 events of colonisation by C4 grasses. These grasses are restricted to open canopy habitats, demonstrating the ancient existence of open canopy areas. Populations of two commonly dominant species, *Loudetia simplex* and *Themeda triandra*, were shown to be genetically distinct from populations outside Madagascar, which suggests these species are probably native. Specimen data for 14,000 collections from the Paris herbarium, held within the Museum national d'Histoire naturelle, revealed that many grasses historically considered to be alien in Madagascar are in fact likely to be native.

From 2011 to 2016, functional ecology research was carried out in collaboration with Professor Peter Linder from the University of Zurich. The phylogenetic diversity and disturbance responses of grassy ecosystems in Madagascar were found to match those observed in natural grassy ecosystems elsewhere. Functional trait research began in 2016, in collaboration with Caroline Lehmann, a senior lecturer at the University of Edinburgh, and a global network of savanna ecologists focused on African savannas has been formed. Malagasy grasses show ancient adaptations to grazing, suggesting the existence of pre-human grazing lawn ecosystems.

Vascular plant diversity surveys carried out in Itremo by Kew Madagascar staff (2010 onwards) have documented 681 vascular plants, 4.5% of which are narrow local endemics (supported by Conservation International). Poaceae diversity surveys (2012–2016) were carried out, and our data suggest that many of these grassy ecosystems could be natural. Fires are a natural driver of ecosystem structure for both open savannas and tapia savannas in both Itremo and Ibity.

At-a-glance

- **Madagascar matters**
  It's the world's fourth largest island and a biodiversity hotspot but its habitats continue to be under threat and degraded.
- **Grasses and grasslands**
  The island is home to 541 species of grass and 40% of these are endemic. Research indicates grasses colonised the island at least 97 times, mainly from Africa, and that the oldest arrived more than 20 million years ago.
- **Rethinking history**
  Early botanists thought the island was originally entirely forested and human activity burned the trees to leave grasslands. We now think many grasses are endemic and the fires are a natural part of their ecosystem. Grass ecosystems now cover 65% of the island.
- **Protected areas**
  Regular fires have always been part of the Itremo and Ibity ecosystems, even though management prohibits them in an attempt to prevent the destruction of nearby forests.
- **A new approach to fire**
  We've been working with managers in Itremo and Ibity to see if controlled fires in the afternoons of the early dry season could clear grass biomass accumulation, thus protecting the forests from hotter fires.

References to the research

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Acknowledgments

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Exploring seed biology to improve agriculture and food security

Summary

Our research and knowledge exchange on the functional traits of native seed has led to direct economic or environmental-efficiency benefits at four seed companies, increased the effectiveness of three genebanks managed by the Crop Trust charity, and affected policy development and implementation in the management of forest genetic resources (FGR) through the Food and Agriculture Organization (FAO) of the United Nations. The research has: affected industry strategies for characterising and using well-adapted seed lots; altered the management of thousands of hectares of agricultural land in the UK and Europe; raised confidence in the seed farming of native species, and increased the security of tens of thousands of banked seed accessions.

Work on comparative seed biology by our researchers has changed agricultural practice, tree species conservation strategies and crop genebank practice.

Impact of the research

Seed production and agricultural practice

Traditionally, agriculture has selected seed lots for performance under managed agronomic conditions without fully characterising or quantifying germination performance and vigour. Our research has shown the importance of thermal time quantification in around 200 plant species (including crops, crop wild relatives and wild plants) from many habitats (arid lands to wet forest; coastal to inland). These findings have changed how seed companies select fit-for-purpose seeds to account for adaptation and resilience to climate change, both in agriculture and in seed farming for restoration.

For example, we worked with Nature's Crops International Ltd (Ahiflower) when they were growing a potential new oilseed crop in the UK, primarily for the export market. They commissioned research from us on understanding the temperature requirements for field germination, as a result they could establish their crop more reliably in the field. In another example, our role in the Native Seed Science, Technology and Conservation project (NASSTEC) has had a beneficial effect on the production of seeds of native plants at Scotia Seeds (Scotland) and has prevented wasted effort through sowing seeds in inappropriate conditions.

Conservation of genetic resources

The conservation of crop and forest genetic resources is challenged by increased human population, land use changes and climate change. These cause, among other issues, losses of forest cover, plant genetic resources and biodiversity. Lack of information and/or uneven application of standards limits the capacity of many countries to develop appropriate policy tools to address issues or to deliver forest and crop genetic resources management. Our research and knowledge on seed-storage traits has significantly influenced policy development internationally in the agriculture and forestry sectors.

Hugh Pritchard acted as consultant on the review of three genebanks, which hold tens of thousands of seed, *in vitro* and cryo accessions. These seedbanks give priority to crops of particular importance to the food security of least-developed countries and get long-term grants from the Crop Trust. The Crop Trust supports the the Global Plan of Action for conserving and using crop diversity through a rational global conservation system, based on the principles of effectiveness, efficiency and transparency.

Background to the research

Our Comparative Seed Biology group have played a pivotal role in the acceptance of seed physiology functional traits as regulatory components of environmental stress and resilience responses. We have moved the analysis of seed functional traits beyond the measurements of seed mass that are favoured in global databases.

Working with a core group of collaborators in more than ten countries, we have shown that interspecific variability in the environmental regulation of germination performance can be quantitatively related to the macroenvironments identified by the Intergovernmental Panel on Climate Change (IPCC). Variation in responses to temperature, water availability and stress explains the existence of niche (micro-)environments for regeneration, and establishes a basis for the selection of fit-for-purpose seed lots by the seed industry. Our group also established that traits that affect seed viability (including traits such as water loss in recalcitrant seeds, survival or persistence in the soil seed bank, or dry-seed-accelerated ageing) are dependent on cellular oxidative status, which is determined by a mechanism that is conserved across a broad phylogeny of plant and fungal orders. Finally, our group was crucial to the development and application of a probabilistic model for the desiccation sensitivity of tree seed (which depends on both seed coat ratio and seed mass) and to identifying appropriate emerging technologies for the storage of tree seeds, specifically cryopreservation.

Since 2012, we have carried out four consultancies, undertaken collaborative research and knowledge exchange with five seed companies under two EU Framework competitive research grants, been involved in implementing FAO policies for the conservation of forest genetic resources, and published 50 papers on seed functional traits (half on germination and half on stress tolerance or survival).

In brief, our research has shown that the environmental imprint on seed germination traits has relevance to agricultural production in requiring the selection of more appropriate seed lots. We developed and promoted seed thermal time characterisation in crop wild relatives. Hugh Pritchard led the translational biology work programme of the EcoSeed project. The seed biology of native species underpins advances in seed farming for habitat restoration. Hugh Pritchard led the science programme of the NASSTEC Initial Training Network project involving the training of 11 PhD students and working collaboratively with three seed companies. The research culminated in a Biological Reviews paper. New ecological information on tree seed desiccation sensitivity, combined with evidence on the benefits of cryopreservation as an emerging technology, has transformed conservation strategies for forest genetic resources. A probabilistic model on Panamanian trees developed in the group has been widely applied to the world's floras (specifically to those of Australia, Brazil and China) and is cited, along with other work from the group, in the FAO report *The State of the World's Forest Genetic Resources*. Finally, the identification that oxidative status is a universal measure of stress in seeds that is highly conserved in cells of many orders of plants and fungi, has led to acceptance that all seeds die eventually – even in the world's gene banks – and a reappraisal of bank management.

At-a-glance

- **Why does it matter?**
  Knowledge of seed biology is central not only to understanding plant regeneration and ecosystem resilience, but also to conservation, global agriculture and food security.
- **What is studied?**
  We study functional traits in wild plant species, especially those related to germination, longevity and stress. Using the latest lab-based techniques, we test the effects of environmental variables such as temperature, water and salinity on germination. These variables have significant implications for species distributions and extinction risk.
- **Who uses the research?**
  Kew is an important resource for research, conservation, restoration, reforestation and crop breeding. External stakeholders include scientific institutions, governments, agricultural and technology companies, and the food, timber and pharmaceutical industries.
- **Priorities at Kew**
  We study extreme environments, seeking the most stress-tolerant seeds to inform our understanding of seed lifespan. Our research addresses solutions for today's global challenges, including climate change. Over the next ten years, Kew aims to bank 50% of all priority crop wild relatives and 60% of all tree species that are storable.

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Acknowledgments

Generously supported by the Crop Trust, the European Union's Framework Programme, FAO, Nature's Crops International Ltd and the Newton Fund.

Our research and knowledge on seed-storage traits has significantly influenced policy development internationally in the agriculture and forestry sectors.

Explaining forest health through fungal diversity

Summary

Fungi that form mutual partnerships with plant roots are known as mycorrhizal fungi. In Europe's forests, nearly every root of every tree species is covered by so-called ectomycorrhizal fungi. We have estimated fungal diversity in soils across the dominant tree species in Europe, from southern Italy to northern Finland, and from Spain to Romania. The results shine a light on which of these fungi grow where, and why, and the impact of pollution on their activities. Our results have been widely published in specialist journals, mainstream science publications such as *Nature* and in a report by Plant Life/Plant Link to increase awareness of the threats to these fungi and the trees that depend on them.

The importance of soil, and the organisms that live within it, has been known for many years. However, until recently, it has not been possible to reveal how tree roots work with soil organisms. Thanks to advances in molecular ecology, we are now able to link pollution with fungal changes at a large scale for the first time. Since 2018, Kew and Imperial College scientists have been able to show the distribution, abundance and tree host preference of a major group of forest soil organisms, across the whole of Europe.

We study ectomycorrhizal fungi – those that grow in mutual partnership (symbiosis) with plant roots. Deep down in Europe's forest soils, nearly every root of every tree species is covered by a fungus. The fungus does the hard work of taking up water and nutrients from the soil, uses some for itself, and passes the rest to the tree root. As payment, the root gives some of the power it gets from photosynthesis to the fungus. Many of these fungi are very large and long-lived; some individuals can occupy several square metres of forest ground and live for decades.

Until recently it has not been known how these fungi manage to survive, how many different species there are, or where they grow. Previously, the only way for us to understand diversity and distribution was to observe mushrooms appearing on the soil surface in autumn – but not all fungi reproduce above ground. In collaboration with one of the largest environmental monitoring networks, ICP Forests, and with support from the UK Natural Environment Research Council (NERC), we analysed 40,000 roots from 13,000 individual soil samples across European forests. Using DNA technologies, we identified the fungi that were symbiotically associated with beech, spruce, pine and oak in 137 sites.

Impact of the research

We have used molecular ecology to open up the soil 'black box' and to link pollution with mycorrhizal changes at a large scale for the first time. This will have a major impact in the future. In 2018, our results were the subject of a six-page article in the top general scientific journal *Nature*. This was covered by 30 news outlets worldwide, and has already been cited by 34 other scientific publications.

The detrimental impact of high nitrogen pollution on the diversity of ectomycorrhizal fungal species was cited in the Plant Life/Plant Link UK 2017 report *We Need to Talk about Nitrogen*. This raised awareness of the challenges of nitrogen pollution both among the general public and throughout government and what steps could be taken to mitigate against the damage.

Our research also has more specific impacts on forest monitoring, environmental policy and conservation science.

Background to the research

Research into ectomycorrhizal fungi at Kew was started in 2006 by Martin Bidartondo with a NERC PhD student Filipa Cox. She published the first large-scale analysis of Scots pine forests and their mycorrhizal fungi in Britain and Germany. The results showed that nitrogen pollution was negatively affecting the diversity of fungi that trees could rely on; a few fungi appeared to thrive in disturbed conditions but most lost out. The 'toolbox' for trees becomes less diversified in polluted areas.

This finding led to a Marie Curie fellowship at Kew and Imperial College London by Laura Martinez-Suz. As an expert on oak mycorrhizas, Laura sampled 22 oak monitoring plots across nine European countries, with additional support from the Bentham-Moxon Trust. This major study showed that nitrogen pollution is also negatively affecting oak forests at an even larger geographic scale. The fungi that lose out are those that can mine at long distances from the tree root and use organic sources of nitrogen.

Research continued and by 2018 we were able to show the distribution, abundance and tree-host preference of ectomycorrhizal fungi, across the whole of Europe. This research investigates how the diversity and distribution of ectomycorrhizal fungi is influenced by soil factors, climate, air pollution and tree host characteristics. This continued our collaboration with ICP Forests, with support from the UK NERC for post-doctoral fellow Sietse van der Linde.

Estimating fungal diversity across different tree species and geographic zones, from southern Italy to northern Finland, and from Spain to Romania, we have a transformed understanding of which mycorrhizal fungi grow where, and why. We found environment and tree characteristics can explain mycorrhizal diversity at large scales, that the pollution thresholds used as major ecosystem assessment tools need strong downward adjustment, and that mycorrhizal specificity and plasticity have been underestimated.

What next?

Our research continues to have an impact on the understanding of European forests. For example, in March 2019 we presented our proposals for the first-ever biodiversity assessment in the context of the Third Pan European Forest Soil Survey in 2020–2025. In future, our research could lead to the first large-scale biological monitoring of forest soils.

At-a-glance

- **Unearthing soil's secrets**
  The work of tree roots used to be a mystery but it turns out that they contract out most of their 'mining' activities to fungi – they are better at it.

- **A change in the air**
  In 2004, ICP Forests became interested in how the partnership between trees and fungi was reacting to increased levels of carbon and nitrogen in the atmosphere. Could fungi warn us of changes before tree damage was seen?

- **Pines and oaks**
  Our research on Scots pines and their fungi started in Britain but was then extended to Germany. We found that nitrogen pollution was negatively affecting the diversity of fungi that trees could rely on. Work on oak mycorrhizas across nine European countries then showed similar results over a much wider area.

- **Gathering more data**
  By 2018 we had analysed 40,000 roots from 13,000 individual soil samples across European forests to identify the fungi that were symbiotically associated with beech, spruce, pine and oak in 137 intensively monitored forest sites.

- **Spreading the word**
  Significant publications in 2017 (Plant Life/Plant Link) and in 2018 (*Nature*) raise awareness of the importance of ectomycorrhizal fungi and the threats to them and their trees.

References to the research

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www.kew.org Read & Watch

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We have opened up the soil ‘black box’ and linked pollution with below-ground changes in ectomycorrhizas on a large scale for the first time.

Plant conservation

Reintroducing the lady's slipper orchid to northern England

Cypripedium calceolus

Summary

Our extensive research on the iconic lady's slipper orchid (*Cypripedium calceolus*), which is critically endangered in the UK, has guided its successful reintroduction into 12 sites in northern England. We developed new strategies for *in vitro* propagation of *C. calceolus* and for the use of genetic markers to ensure that all reintroduced plants come from an appropriate English source. We have also gained an improved understanding of the fungi this orchid depends on and are expanding the impact of our research through collaborative studies with colleagues from across the range of the species. Our ongoing research and our membership of the *Cypripedium* Committee will inform the long-term management of the reintroduction sites by Natural England.

Cypripedium calceolus (lady's slipper orchid) has one of the widest distributions of any orchid, occurring from northern England to eastern Russia and from northern Scandinavia to the Pyrenees. Despite this wide range, it is threatened in many countries, and it has legal protection throughout Europe. Following our work in support of the reintroduction of the species in England, we have built up a network of collaborators across the range of the species, and genetic data are now being incorporated into conservation plans for this species in England, Denmark, Estonia, Finland, Italy, Romania and Russia.

Impact of the research

Our role in the reintroduction of *C. calceolus* in England has involved research into propagation methods, mycorrhizal fungal associations and genetics, in addition to the production of seedlings that are transferred to a network of growers to be grown on before planting out. This network is managed by Natural England, the government's advisory body for the natural environment. The first flowering of a reintroduced plant occurred in 2000; by 2017, reintroduced plants produced nearly 700 shoots in total, and more than 200 flowers were counted across nine reintroduction sites. Members of the public are actively encouraged to visit two of the reintroduction sites at flowering time to publicise the success of the project and take pressure off the wild site.

To date, all the seedlings passed on to Natural England have been produced using *in vitro* asymbiotic germination, but ongoing research into symbiotic germination is progressing. Using isotope studies, we have demonstrated that, after planting out, asymbiotically produced seedlings establish mycorrhizal associations that are indistinguishable from those of wild plants.

A member of our staff sits on the *Cypripedium* Committee (chaired by Natural England) which coordinates work on this species in England, setting priorities for seed production for propagation, identifying potential sites for introduction and overseeing the conservation of this species in England.

Other orchid species have also benefitted from the model developed for *C. calceolus*, and we have conducted research, for example, in support of the conservation management of *Liparis loeselii*, *Dactylorhiza* species, *Ophrys* species and *Cephalanthera* species in the UK.

As a result of the impact of our work on *C. calceolus* and other orchids, we were asked to conduct a global Red List assessment of all slipper orchids (about 180 species). This study showed that around 90% of these species are threatened.

Background to the research

Orchids can be propagated on sterile media with the help of symbiotic fungi (symbiotic propagation) or without (asymbiotic propagation), but because of the complexity of symbiotic relationships, asymbiotic propagation is generally attempted first. Techniques for the asymbiotic propagation of *Cypripedium calceolus* from seed were originally developed at Kew in the 1990s by staff in the Micropropagation Unit. These techniques have been refined to allow the production of seedlings for the *C. calceolus* reintroduction programme led by Natural England. Recently, research has been initiated to investigate the possibility of developing symbiotic propagation techniques. Since 1990 we have provided training in the hand pollination of *C. calceolus* to Natural England staff and associates, enabling the production of seed of known background for the propagation programme.

This orchid species is popular in horticulture, so it is not clear whether all the plants thought to be of native origin are actually derived from an English source. From 2000 to 2018, we developed genetic markers to clarify the origin of all plants that could potentially be involved in the propagation programme. The development of markers was initially hampered by the large genome size of this species and initial studies were therefore based on variation in the DNA markers that allow us to produce unique fingerprints for all individuals that are thought to be native English plants, and to identify some individuals as introductions from elsewhere.

These genetic data also drive the production of seeds of known genetic background, with only 'wild × wild' seedlings being introduced at the remaining wild site and more genetically variable material being planted at reintroduction sites.

For reintroduction to be judged successful, it is important to demonstrate that the plants are functioning ecologically like natural plants and for there to be natural regeneration at the reintroduction sites. This species has long generations so, as yet, there has been insufficient time for natural regeneration to occur. Nevertheless, in 2017 to 2018 we demonstrated that the plants at the reintroduction sites, despite having been produced asymbiotically, have established associations with mycorrhizal fungi post-planting and have nitrogen and hydrogen isotope signatures that are indistinguishable from those of wild plants.

What next?

Since 2018 our genetic studies have been expanded to include material from across the range of the species, and we are now developing *C. calceolus* as a model species for studying the balance between clonal and sexual reproduction and the impacts of this on biogeography and population demographics. Since 2010 we also provide genetic data to support plans for conservation management in several other countries.

At-a-glance

- **Iconic orchid**
  The characteristic slipper-shaped lip of the flower make these orchids, members of the Cypripedioideae, easy to recognise.
- **Popular but under threat**
  There are many species and hybrids are available in the horticultural trade for the garden or the house. Despite this popularity, many species are threatened with extinction in the wild.
- **Red Listing**
  A Red List assessment is a way to evaluate how threatened a species is so steps can be taken to conserve it. Kew is leading on assessing slipper orchids.
- **First results**
  Slipper orchids are divided into five genera. *Cypripedium* (52 species) is the most widespread of these genera, occurring in North and Central America, Europe and Asia. Assessments for all five genera have been published.
- **In danger**
  The *Cypripedium* Red List assessments made shocking reading with many species either endangered or critically endangered.
- **Hope dies last**
  Due to improved propagation methods, it is hoped there will be a reduction in collecting from the wild. In the meantime, we are working on different conservation measures including reintroduction.

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Acknowledgements

We acknowledge support from Natural England and from The Sainsbury Orchid Trust Fund which facilitated the project on the native lady's slipper orchid.

The public are actively encouraged to visit two of the reintroduction sites at flowering time to publicise the success of the project.

Cypripedium margaritaceum

Building a global seed-bank partnership

Kew scientist collecting grass seed

Summary

The network of 160 organisations in 96 countries and territories within Kew's Millennium Seed Bank Partnership (MSBP) is the largest *ex-situ* plant conservation initiative in the world. By December 2018 our technology transfer and capacity-building programme enabled the conservation of high-quality seed of 45,315 wild species to MSBP seed conservation standards. We use Kew expertise to inform species prioritisation and targeting, the design of seed banks and collection programmes, viability testing, and the use of collections. Our internationally recognised training programme ensures that partners acquire the knowledge and skills necessary to collect high-quality seed, herbarium vouchers and associated data. This training enables future research and strengthens the partnership.

Kew's Millennium Seed Bank (MSB) is the largest and most diverse wild-species seed bank in the world. Seeds from more than 39,000 species of plants are stored in the underground, climate-controlled vaults in the Sussex countryside. The MSB has an associated global network, a team of scientists, botanists, technicians, educators and collectors who form the Millennium Seed Bank Partnership (MSBP). This network of partners from 96 countries and territories works to build seed banks around the world to conserve species in their countries and regions of origin. In addition to collecting and banking seed, a well-established training and skills transfer takes place, enabling the best practices, technology, and ideas to be shared by everyone involved.

Impact of the MSBP

Predicting seed storage behaviour

Our storage behaviour predictor model has already been used in at least 19 partnerships (Argentina, Armenia, Bhutan, Bolivia, Chile, Colombia, Costa Rica, Dominican Republic, Fiji, Georgia, Hawaii, Indonesia, Jordan, Mexico, New Zealand, Pakistan, Peru, Taiwan and Thailand), significantly improving collecting efficiency by highlighting species that require alternative storage. The Thailand Global Tree Seed Bank project provides the following example. A target list of 1,100 tree species was produced using the best information available on seed-storage behaviour. When re-analysed using the predictor tool, 22% (244) of species changed their status from likely orthodox (storable) to likely recalcitrant (not storable in conventional seed banks).

Improving collection rates

Collection guides produced through the Crop Wild Relatives project (CWR) enable partner countries to collect 80% of their target taxa. This contrasts with a similar project in a country where the participants received full training and technical support but no collection guide (because of lack of funding). In that project, only 53% of target species could be found and collected.

Raising standards

Kew-led Seed Conservation Standards Reviews have been completed for more than 15 partners. Most have changed their practice based on the evidence gathered. Communicating through the MSBP questionnaires that are sent out across the partnership annually, 73 partners have requested reviews in the coming years. The MSBP Standards have been incorporated into MSB training materials, resulting in changes to the working practices of partner institutes.

Seed conservation training

From 2015 to 2018, the MSB provided training for 283 seed conservation scientists and technicians from 63 countries through the CWR project. In year three of this project, 56% of participants were female and 44% male. In addition, 74.5% of participants in the overall project were from Least Developed, Low Income and Lower Middle-Income countries, as defined by the Organisation for Economic Cooperation and Development (OECD). As a result of this training, Kew received 3,477 CWR collections from 21 countries, representing 94% of the target 3,713 collections, with the seed-collecting guides undoubtedly having contributed to this success. This reflects the norm for MSB training, which is tailored to participant needs, has impact in the workplace, and results in improved collection quality. The availability of high-quality collections from the MSB and partners is an indicator of the success of the training programmes offered.

Better equipment

Seed bank design support has enabled partners to maximise their use of space and budget while ensuring that equipment of appropriate specification is installed and workflow is built into the design. At least seven new international seed banks have received help in the past six years, leading to high quality fit-for-purpose seed banks. The new seed banks are in Colombia, Dominican Republic, Georgia, Indonesia, Singapore, Thailand and UAE. We supplied 19 seed-banking kits to CWR partners, facilitating the collections noted above, and at least 45 kits have been supplied to MSB partners for other projects, enabling over 1,800 additional seed collections to be made in areas previously lacking basic collecting and processing facilities.

Repatriation of value-added data

From 2012 to 2018, taxonomic verifications for 7,569 seed collections were undertaken by Kew botanists and repatriated to MSB partners. Throughout that period, taxonomic names were updated as appropriate for the more than 90,000 live seed collections stored in the MSB by December 2018.

Background to the research

Our MSBP Technology Transfer and Capacity Building programme draws on the following underpinning research, knowledge and tools.

- Knowledge of seed storage behaviour.
- Targeting of collections through the use of population, distribution, collection and seed quality data from Kew's Seed Bank Database (SBD) and the MSBP Data Warehouse, which enables collections research and gap analysis.
- MSBP seed conservation standards have been developed that provide the basis for all technology transfer and capacity building with partners.
- Seed conservation training of collaborating scientists from over 50 countries, acting on data obtained from a Training Needs Assessment process and technical-capacity monitoring.
- The equipment and knowledge transferred to partners ranges from expertise in seed bank design to the provision of seed-banking kits that include appropriate technology solutions for moisture measurement, seed drying and storage in situations without reliable facilities.
- Repatriation of value-added data associated with collections. Through reports to partners and access to the MSBP Data Warehouse, where duplicate collections can be compared, partners benefit from the availability of a range of MSBP data.

At-a-glance

- **Before the MSBP**
  The Millennium Seed Bank opened in 2000. During the first ten-year phase, more than 1,000 people were trained in seed conservation.
- **Going global**
  The MSBP was established in 2010 to build capacity to increase the scale of seed banking globally. Since then, nearly 1,400 more people have been trained, either at the MSB, or by its staff, overseas.
- **Training abroad**
  Courses are run in other countries when we need to train a large number of staff at once. For example, at Cibodas Botanic Garden, Indonesia in April 2017, we trained staff from across the country so they could set up regional seed banks in their own botanic gardens.
- **Keeping up to date**
  Sometimes there is training on new equipment or particular processes, such as the 56 people trained over the past three years at the MSB in how to monitor seed collections.
- **Training is vital**
  It gives more people the skills they need to make and care for high-quality collections of seeds. Seeds which stay alive for longer and have more information stored about them are, ultimately, more useful as an insurance policy against extinction.

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At least seven new international seed banks have received help in the past six years, leading to high quality fit-for-purpose seed banks.

Conserving plant diversity by safeguarding seeds

Summary

Described by Sir David Attenborough as 'perhaps the most important conservation initiative ever', the Millennium Seed Bank Partnership (MSBP) is a long-standing network of seed conservation organisations that are actively safeguarding the seed of wild species from across the world. Over the past seven years, the MSBP has conserved 18,000 species *ex situ* with collections coming from 88% (172) of the world's countries. These species now have a reduced threat of extinction and are held as a significant resource and insurance against global biodiversity loss. The Millennium Seed Bank (MSB) serves as the world's largest repository of wild species for research, education and habitat restoration. Here we outline examples of the conservation impacts and seed use.

Recognised as the largest *ex situ* (seed bank) conservation programme in the world, the MSBP constitutes 160 partners in 96 countries and territories. The MSBP has a significant impact on plant conservation, helping to conserve 15% of global plant species diversity to date (for orthodox, seed-bearing wild vascular plants).

Impact of the research

Collections and species conserved

Over the past seven years, at least 18,128 wild plant species (39,945 collections) have been safeguarded across the MSBP, of which at least 8,661 represent species not previously stored at the MSB. The collections stored at the MSB originate from 172 countries and territories (representing 88% of all countries).

Germination tests conducted

Testing monitors the quality and viability of seed collections, and provides the germination protocols necessary for seed use, restoration and reintroductions. During the review period, 30,391 collections had germination tests, and viability was calculated for each of these collections; 93% of new collections had initial tests accepted.

Contribution to food security and Red Listing targets

The MSB holds accessions for 237 taxa related to 25 of 29 of the world's most important food crops, making a significant contribution to global initiatives.

Partner agreements

During the review period, Kew has had active seed conservation agreements with 131 partners from 69 countries and territories. This includes 69 new partners in 27 new countries who now receive our support for their conservation activities.

Seed use

The collections held at the MSB are available for use and are advertised through the MSB Seed List. Since January 2012, 8,322 collections have been dispatched from the MSB to 280 different institutions around the world for a variety of uses: pure and applied research, environmental purposes, display in botanic gardens and so on.

Collaboration with partners in Kyrgyzstan led to the discovery that an endemic species, *Scutellaria andrachnoides*, has a high content of the anti-cancer agent wogonin. Two European Patent Society patents have now been obtained. Links to *in situ* conservation occur globally with MSB partners using material banked in country. In South Africa during 2013 and 2014, restoration of fynbos was supported by the seed banking process.

Public engagement

Over the review period, there have been 877 press articles about the MSBP, plus active outreach using social media. Our gardens offer an ideal platform from which to reach a wide audience, for example, CWR banana plants from Vietnam were added to our living collection in the Palm House accompanied with information on the importance of conserving the wild relatives of the banana.

Background to the research

Since the 1960s, we have led much of the research that underpins seed conservation best practice. The science of seed-storage behaviour, and in particular the taxonomic and environmental basis for short-lived or desiccation-sensitive seeds, continues to inform seed collection planning and prioritisation, seed processing and seed storage, and the use of alternative techniques. In turn, the viability-testing and use of seeds is informed by research into seed longevity and seed dormancy-breaking. The main techniques used to preserve seed viability, namely drying seeds, sealing them in a container and storing at sub-zero temperatures, are well established for the majority of 'orthodox' plant species. Nevertheless, the application of techniques to achieve the highest possible value of the collections in terms of genetic diversity, viability and germination requires continual research.

Three key projects during the review period illustrate the MSBP's impact. The ENSCONET consortium, developed and led by Kew, involves seed conservation programmes from across Europe. The consortium has responded to EU targets, and by 2017 had banked approximately 63% of Europe's threatened taxa.

The Adapting Agriculture to Climate Change project is a global initiative covering 24 countries that focuses on wild relatives of 29 of the world's most important crops. Since 2013, participants in this project have conserved 237 taxa of crop wild relatives, directly addressing UN Sustainable Development Goals and the International Treaty on Plant Genetic Resources for Food and Agriculture.

The Global Tree Seed Bank project focuses on threatened tree seed conservation and research (including restoration). This project has conserved 2,755 tree species from 34 countries since 2014, while the tree research aims to address key knowledge gaps in tree conservation.

The conservation value of the collections held at the MSB was recently reviewed and they were found to represent a 'high quality, rich biological resource', with substantial taxonomic diversity (365 families, 5,813 genera, 39,669 taxa), from a wide geographic range (189 countries and territories), with high conservation value (73% collections from endangered, endemic or economically important taxa).

Safeguarding plant diversity for future generations is only one impact of the MSBP. Collections both at the MSB and at partner institutes are actively used to improve our knowledge and understanding of seed biology and to address the pressing issues facing humanity, such as food security. The Adapting Agriculture to Climate Change: Collecting, Protecting and Preparing Crop Wild Relatives project has sent 3,218 collections to eight international gene banks. These collections will be used to identify traits of value in crop breeding such as tolerance of heat, drought, salinity and waterlogging, resistance to pests and diseases, resistance to root rot and yield. In addition to the 8,322 seed samples sent from the MSB during the review period, 1,935 seed samples were distributed by at least 18 partners from 14 different countries.

At-a-glance

- **What is seed banking?**
  The main techniques used to preserve seed viability, namely drying seeds, sealing them in a container and storing at sub-zero temperatures, are well established for the majority of orthodox plant species.
- **What does MSBP do?**
  We coordinate the largest *ex situ* plant conservation programme in the world. Based at the Millennium Seed Bank, our team works with partners in the UK and around the globe to conserve the seed of wild plants.
- **Our focus is at-risk species**
  With 60,000 to 100,000 plant species currently threatened with extinction, our priority is those species most at risk – the endangered and the endemic, plus those likely to be most useful in the future.
- **Climate change**
  This presents significant threats to plant biodiversity and seed conversation provides insurance from extinction or threatened species and ecosystems.
- **Tree seeds**
  We are collecting seeds of 3,000 tree species worldwide, among them the world's rarest, most threatened and most useful tree species.
- **Conserving crops**
  Crop wild relative species hold important traits for the development of resilience to the impacts of climate change. Working with partners around the world, we are banking seed collections which cover the wild relative gene pools of the world's 29 major crops.

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The conservation value of the collections held at the MSB was recently reviewed and they were found to represent a ‘high quality, rich biological resource’.

Restoring diversity through seed conservation

Summary

The UK Seed Conservation programme comprises collaborative, multi-disciplinary activities across Kew and more than 50 partner organisations to support the conservation and restoration of threatened UK species and habitats. Our impact is built around the exceptional breadth, depth and quality of the seed collections and associated data held by Kew. These collections and data are available and widely-used for research and conservation, together with an active programme of applied research and knowledge transfer to provide evidence-based advice and inform conservation practice and policy in the UK. Expertise is shared through our diverse network of partner organisations and volunteers, amplifying impact through training, capacity-building, outreach and the development of a nationwide network of skilled seed-collecting teams.

The MSB's UK seed collections, data and research are an exceptional resource for conservation. They support the restoration of threatened species and improve our understanding of the UK's plant genetic resources and their role in responding to the socio-economic and ecological pressures facing our natural environment.

Impact of the research

Making materials available

Between 2015 and 2019, 1,455 samples from the UK collections were dispatched via the MSB Seed List 1,062 were for research, 200 to develop living collections at Kew and other botanic gardens, and 193 for environmental purposes including regeneration. Access to scientific expertise and larger quantities of seed is provided by the UK Native Seed Hub (UKNSH). Between 2012 and 2018, the UKNSH provided plant materials or technical advice to 57 projects involving 37 organisations including Natural England, the National Trust and the South Downs National Park.

Providing evidence-based solutions

We bring together Kew's strengths in seed banking, germination ecology, propagation, horticulture and conservation genetics. For example, Kew is a delivery partner for Colour in the Margins, part of the Back from the Brink species recovery programme highlighted in Defra's 25 Year Environment Plan. In 2018, we regenerated seed of five threatened arable species and developed detailed propagation methods for ten such species including *Galeopsis angustifolia*, *Adonis annua* and *Veronica verna*. Seed and propagation methods are now in use to plan and implement reintroductions.

Sharing knowledge

We work with a diverse range of partners, amplifying impact and building capacity for the effective use of seed and plant genetic resources. For example, since 2013, the UK National Tree Seed project (UKNTSP) has built a collecting network of over 420 individuals and associated volunteer groups, providing training to over 200 seed collectors. In 2018, a restoration training day was piloted for 20 National Trust staff. Now training is being rolled out nationally. In 2018, two seed-collecting training courses were delivered as part of our contribution to Back from the Brink. Eight threatened arable species were collected for reintroduction use and long-term conservation in the MSB. We led the development of a UK Forest Genetic Resources strategy between 2017 and 2018, working with partners to establish a framework to understand, protect and use the genetic diversity of the UK's trees. This work has been recognised in the Defra Tree Health Resilience Strategy and as a contribution towards achieving Aichi Biodiversity Target 13 of the Convention on Biological Diversity (CBD).

Background to the research

A peer-reviewed assessment of seed conservation work in the UK identifies how we have helped to overcome key seed-related constraints to effective conservation by: safeguarding species and genetic diversity in *ex situ* seed collections; making this material and the associated data available for research, conservation and restoration; undertaking research to provide evidence-based solutions to problems in conservation practice and policy; and sharing knowledge and building capacity for effective seed-based conservation. These impacts are made possible by the unique breadth, depth and quality of our seed collections and associated data.

The UK Flora project

This continues to secure collections from the broadest possible range of specie both native and archeophyte (non-native species naturalised in the UK prior to AD 1500). By December 2018, 7,805 wild-origin and cultivated UK collections were held in the MSB, representing 1,963 native and archeophyte taxa. This represents 98% of the UK's bankable native flora at species level, including 80% of threatened taxa, enabling the UK to make good progress towards meeting the CBD Aichi Biodiversity Targets 12 and 13 and we have also met Target 8 of the Global Strategy for Plant Conservation.

UK National Tree Seed project

Recent work has placed an increasing emphasis on multiple-origin collections, capturing intraspecific diversity within and between UK plant populations. Since 2013, UKNTSP has developed and applied a novel sampling strategy to capture genetic diversity at national, eco-geographical and individual mother-plant scales. Modelling approaches developed in collaboration with Morton Arboretum in Chicago suggest that this strategy captures >90% of alleles present in UK populations of *Fraxinus excelsior*, a conclusion that is supported by molecular testing of *Taxus baccata* collections and their maternal trees by Kew researchers. By the end of 2018, collections had been made for 74 species, with multiple-origin samples for 43 – a total of 1,166 collections from over 9,000 individual trees. The importance of the UKNTSP in contributing to national and international conservation targets is highlighted in the sixth national report to the CBD, with particular reference to Aichi Biodiversity Target 13.

Setting international standards

The quality of our seed collections and data reflects the leading role that the MSBP has taken in setting international standards for wild seed conservation. By the end of 2018, all UK collections large enough for testing had an 'accepted' viability test, with 76% achieving at least 80% viability. Detailed field data are available for UK collections, including species name (100%), location (98%), habitat (87%) and population size (73%). Ongoing research at the MSB seeks to improve seed-banking practices and to make seed available for use by determining the longevity of native seed, improving cryopreservation protocols, developing new dormancy-alleviation techniques, and increasing species capture and seed viability in mechanised harvesting.

At-a-glance

- **Our three key projects**
  Our UK team delivers three closely-related projects: the UK Flora project, the UK National Tree Seed project and the UK Native Seed Hub.

- **Banking the UK's native flora**
  The UK Flora project has banked 98% of our bankable, seed-bearing native flora and is working with botanists to bank the very tricky final species. We continue to increase the number of collections conserved from threatened species and build on the genetic diversity of these collections.

- **Trees under threat**
  Many species, particularly trees, are under significant threat from an increasing number of pest and disease outbreaks. The UK National Tree Seed project captures genetic diversity for the woody flora of the UK.

- **Restoring UK habitats**
  The UK Native Seed Hub increases the quantity, quality and diversity of native plants and seeds available for conservation and habitat restoration in the UK landscape. We supply high-quality seed and plug plants of known origin together with technical advice for reintroduction and restoration projects.

- **Sharing seed know-how**
  We work with over 60 partners across the UK, and regularly share scientific, technical and practical skills in order to raise the capacity across the UK for seed collecting, banking and use.

References to the research

This summary was based on an impact paper 'Conserving, understanding and restoring plant diversity in the UK'.

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By December 2018, 7,805 wild-origin and cultivated UK collections were held in the MSB, representing 1,963 native and archeophyte taxa.

Adonis annua

Identifying Tropical Important Plant Areas and promoting their protection

Summary

Tropical Important Plant Areas (TIPA) provide an effective tool for prioritising plant conservation efforts in the tropics. Initiated in 2015, the TIPA programme is already having an impact in seven countries. It guides and directly influences conservation planning, policy and management, and raises the profile of the importance of plant species and habitats both nationally and globally. Early successes have resulted in expressions of interest in adopting the TIPA approach from several countries across the tropics. TIPA help deliver Target 5 of the Global Strategy for Plant Conservation, addressing the world's biodiversity and environment crisis under the United Nations' Convention on Biological Diversity.

As many as 20% of the world's plant species are threatened with extinction and many of these species occur in the tropics, where existing legislation, protected area networks and land use practices frequently fail to protect plant resources adequately. Accessible information on plant species and habitats and their distributions is often not available to policy makers, hence plants are poorly represented in conservation strategies despite their fundamental importance to humans and wider biodiversity.

With resources for plant conservation so scarce, a means of effectively prioritising plant conservation efforts is urgently required – the Important Plant Areas (IPA) model provides a scientifically rigorous, yet readily achievable, methodology for achieving this goal.

Impact of the research

For our TIPA programme, we focus on seven countries or regions where we have strong existing partnerships and robust data sets: Bolivia, the Caribbean UK Overseas Territories, Cameroon, Guinea, Indonesian New Guinea, Mozambique and Uganda (2015–2020).

The first stage for each country is to build the evidence base to identify TIPA, but we have already made impacts in the following four key areas.

Influencing government

This delivers increased protection and national recognition for TIPA and the species and habitats they support. In the British Virgin Islands our suggestions for designating Environmentally Sensitive Areas and Environmentally Sensitive Species have government approval. In Cameroon, botanical surveys and an associated national plant Red Listing programme provided crucial evidence towards the gazetting and proposed creation of new protected areas: the Bakossi National Park, Mount Cameroon National Park and the proposed Kupe and Muanenguba Integral Ecological Reserves.

Informing site management

Botanical information is a valuable input into the effective management of important sites for biodiversity. In Guinea, we, with others, have provided essential botanical information for the revised management plan for the proposed Moyen Bafing National Park, one of 22 Guinea TIPA sites. In Mozambique, evidence on the botanical importance of the Ribaue Massif helped prioritise this mountain range as a candidate for community-led conservation and sustainable management efforts.

Increasing awareness

We promote the importance of plant species and habitats, both globally and nationally. For example, *The National Flower* campaign has raised awareness of wild plant species in Guinea. A series of regional and national workshops selected a national flower *Vernonia djalonensis,* this is a Critically Endangered narrow endemic of Guinea. It grows within the Bowal Tankon and Bowal Touppe Mama TIPA and is now subject to a conservation action plan that links the national flower campaign to on-the-ground conservation action.

Involving other tropical countries

We promote and disseminate the programme and its national results through discussions with our global networks and via international conferences and workshops. Many other tropical countries are looking to adopt the TIPA methodology and we have had several formal requests for a joint programme, for example, from Ethiopia. This highlights the increasingly global impact of the TIPA programme.

Background to TIPA

Identifying Important Plant Areas (IPA) and promoting their protection and sustainable management are critical steps towards meeting Target 5 of the Global Strategy for Plant Conservation (GSPC): *'At least 75 per cent of the most important areas for plant diversity of each ecological region protected with effective management in place for conserving plants and their genetic diversity'*.

The process also facilitates other GSPC commitments and so feeds into the implementation of the Convention on Biological Diversity and the UN Sustainable Development Goals.

Led by Plantlife International and its partners, the Important Plant Area (IPA) model has been highly successful in delivering targeted plant conservation within the European Union and the Mediterranean region. To date no IPA projects have been completed in the tropics, greatly hindering the ability to achieve GSPC Target 5 globally.

We launched the TIPA programme to address this critical knowledge gap. We have worked closely with Plantlife International, existing IPA partnerships and many partner institutions to review and revise the IPA criteria so that they are readily applicable in the tropics and address the key plant conservation issues in these regions. This work was a truly international endeavour, involving twenty authors from nine countries, underpinned by a global consultation on the revised criteria.

Working together with our in-country partners, we are now identifying and documenting areas that support globally threatened plant species, as well as habitats and concentrations of important species including those of high socioeconomic value. The designation of TIPA, and the provision of data and recommendations relevant to these sites and their species, enables national authorities to prioritise the protection and sustainable management of their natural resources effectively, a process that is supported by our in-country partners.

What next?

The TIPA programme is still in its relatively early stages, yet we are already achieving significant outcomes for plant conservation, building on our experience and that of our partners in the tropics in identifying sites of critical importance for plants. Our aim is that the TIPAs model will be applied more widely across the tropics so that a global network of threatened sites can be identified in the future.

At-a-glance

- **Extinction threat**
  One in five of the world's plant species is threatened with extinction. Many of these are in the tropics due to continued natural habitat destruction and other development.

- **Tailor-made for the tropics**
  We identify concentrations of threatened species in the tropics and designate them as Tropical Important Plant Areas (TIPA). This helps the relevant national authorities prioritise the conservation of threatened species.

- **Our TIPA programme**
  We have started with seven tropical countries where we already have strong partnerships and good data: Cameroon, Guinea, Mozambique and Uganda in Africa; Bolivia and the Caribbean UK Overseas Territories (firstly British Virgin Islands) in the Americas and New Guinea in Asia. We aim, with our partners, to have TIPA assessed and mapped in these tropical countries by 2020.

- **The bigger picture**
  Our work on TIPA builds on the Important Plant Areas (IPA) initiative, established by Plantlife International, that has been an effective model in the EU and Mediterranean region. Both help with global efforts towards Target 5 of the GSPC.

References to the research

This summary was based on an impact paper 'Tropical Important Plant Areas (TIPAs)'.

More information on the TIPA projects in each country can be found at **www.kew.org**.

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This interactive content, delivered through the Google website and using Google Earth imagery as a backdrop, has introduced the TIPA programme to a wide general audience.

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This work was a truly international endeavour, involving twenty authors from nine countries, underpinned by a global consultation on the revised criteria.

Evaluating the global extinction risk of plants

Fleurydora felicis – an Endangered Guinean species

Summary

The *Red List of Threatened Species* is the most comprehensive, and authoritative source of global extinction risk assessments. It supports biodiversity research, conservation planning and international conservation policy, and influences funding and business decision-making. Red List coverage includes less than 10% of plant species, a data gap that severely limits the effectiveness of plant conservation worldwide. In April 2019 Kew had assessed or reviewed 29% of the assessments on the current list. We are accelerating the rate at which plant extinction risks are assessed because the sooner threatened plants are on the Red List the greater the chance of reversing their decline.

Our response to the global biodiversity crisis is to raise the profile of threatened plants. We harness the International Union for Conservation of Nature (IUCN) Red List to assess plant extinction risk, which in turn influences policy, changes business practices and avoids extinctions. Most plants are currently not represented on the Red List, but our research on threats to plants, commitment to building capacity, technical innovation and expertise has accelerated the rate at which plant extinction risks are assessed.

Impact of the research

Influencing

We reach broad audiences through extensive media dissemination, individual discussions with NGOs, policy-makers and businesses, presentations at workshops and conferences, and formal and informal training delivered at Kew and internationally. We are a founding member of the Red List partnership (2010) and are represented on management and technical committees that drive improvements in coverage and standards.

Raising awareness

The results of our sampled approach to a Red List Index for plants received a Citation of Excellence from the IUCN's Species Survival Commission. The paper by Brummitt et al. (2015) has been cited 93 times. Our headline '1 in 5' statistic featured prominently in *Kew's State of the World's Plants* report for 2016, attracting significant media attention, and continues to be used widely. We regularly promote plant conservation stories when Red List updates are published.

Red Listing rates accelerated

Building on algorithms developed at Kew, the free web resource GeoCAT has supported thousands of assessments and is incorporated in Red List training. Over 150 scientists have been trained to apply Red List criteria; six Kew staff are IUCN-trained trainers. Kew is recognised as a centre of excellence for Red Listing. Funding from the Toyota Motor Corporation in partnership with the IUCN enabled the creation of our Plant Assessment Unit (PAU). Since its establishment in late 2016, PAU has already facilitated the completion of more than 2,000 Red List assessments, including those for wild relatives of crops such as bananas, coffees and yams.

Adding to the Red List

29% of all plant assessments on the 2018 Red List were assessed or reviewed by a Kew scientist.

Extinctions avoided

The International Finance Corporation (IFC, part of the World Bank Group) requires clients to use the Red List to inform project risks. Specifically, the IFC proscribes activities leading to a net reduction in global and/or national or regional populations of Critically Endangered (CR) or Endangered (EN) species over a reasonable period. Thus, Red Listing species as CR or EN improves their survival prospects. For example, in mid-2012, we found and assessed four threatened species – *Tarenna hutchinsonii* (CR), *Stylochaeton pilosus* (EN), *Marsdenia exellii* (EN) and *Raphionacme caerulea* (EN) – on two coastal inselbergs at Rio Tinto's (SIMFER SA) intended new port site at Senguelen, Guinea. As a result, Rio Tinto changed their construction plans to avoid these species, and funded programmes to bank their seed and to develop propagation protocols for them.

Recognition of Tropical Important Plant Areas

Red List assessments undertaken at Kew in collaboration with national partners have underpinned the recognition of 40 TIPA (See 'Tropical Important Plant Areas' case study page 42).

Background to the research

The first Red Lists for plants were produced at Kew and thereafter we have been involved through Red List Authorities and/or specialist groups. In April 2002, Parties to the Convention on Biological Diversity (CBD) committed to achieve, by 2010, a significant reduction of the current rate of biodiversity loss and deliver the sixteen 2010 targets of the Global Strategy for Plant Conservation (GSPC).

We reviewed options for measuring trends and chose a sampled approach, implemented as the Sampled Red List Index, to improve the representation of plants in policy, planning and action.

The importance of herbarium specimens and new research tools was demonstrated by Justin Moat, Eimear Nic Lughadha, Alan Paton and Steve Bachman, together with other researchers.

Research at Kew showed that:

1. Herbarium specimens represent vital information sources for extinction risk assessments.

2. Herbarium specimen data can underpin baseline estimates of global extinction risk in plants.

3. User-friendly tools for calculating key range metrics stimulate Red Listing activity. The free web resource 'GeoCAT' catalysed thousands of specimen-based Red List assessments.

4. Between 10–15 herbarium specimens suffice for reliable assessments of species' extinction risk.

5. Extinction risk assessments based primarily on range size and threats are robust.

6. One in five plants is threatened with extinction.

Our research has established herbarium specimens as vital resources for Red List assessment and has transformed Red Listing methods for plants. GeoCAT has been incorporated into BRAHMS data management software and has been widely adopted by the IUCN Red List Unit and specialist groups, NGOs, natural history museums and herbaria. Red List assessments of random samples of plants resulted in a baseline assessment and an indicator that responds at the highest policy level, such as the CBD and UN Sustainable Development Goals targets.

At-a-glance

- **Red alert**
  The global Red List is used to assess the extinction risk of plants, animals and fungi across the globe. One in five plant species are threatened with extinction.

- **We fight plant extinction**
  How do we know what species to fight for? By researching how threatened species are and adding them to the global Red List.

- **Plant Assessment Unit**
  This team uses Kew's expertise and collections to support the assessment of species for the Red List.

- **Help from the Herbarium**
  Plant collections held in Kew's Herbarium tell us where a plant was located at a specific time. We use these along with tools like Google Earth and site visits to help determine the extinction risk faced by that species today.

- **After assessment**
  Species are given a category based on their likelihood of extinction from Least Concern (no or very little risk of extinction) to Critically Endangered (highest risk of extinction).

- **More than a list**
  The Red List provides information collected during the assessment that is vital for the conservation of that species.

References to the research

This summary was based on an impact paper 'Plant Red Listing at Kew'.

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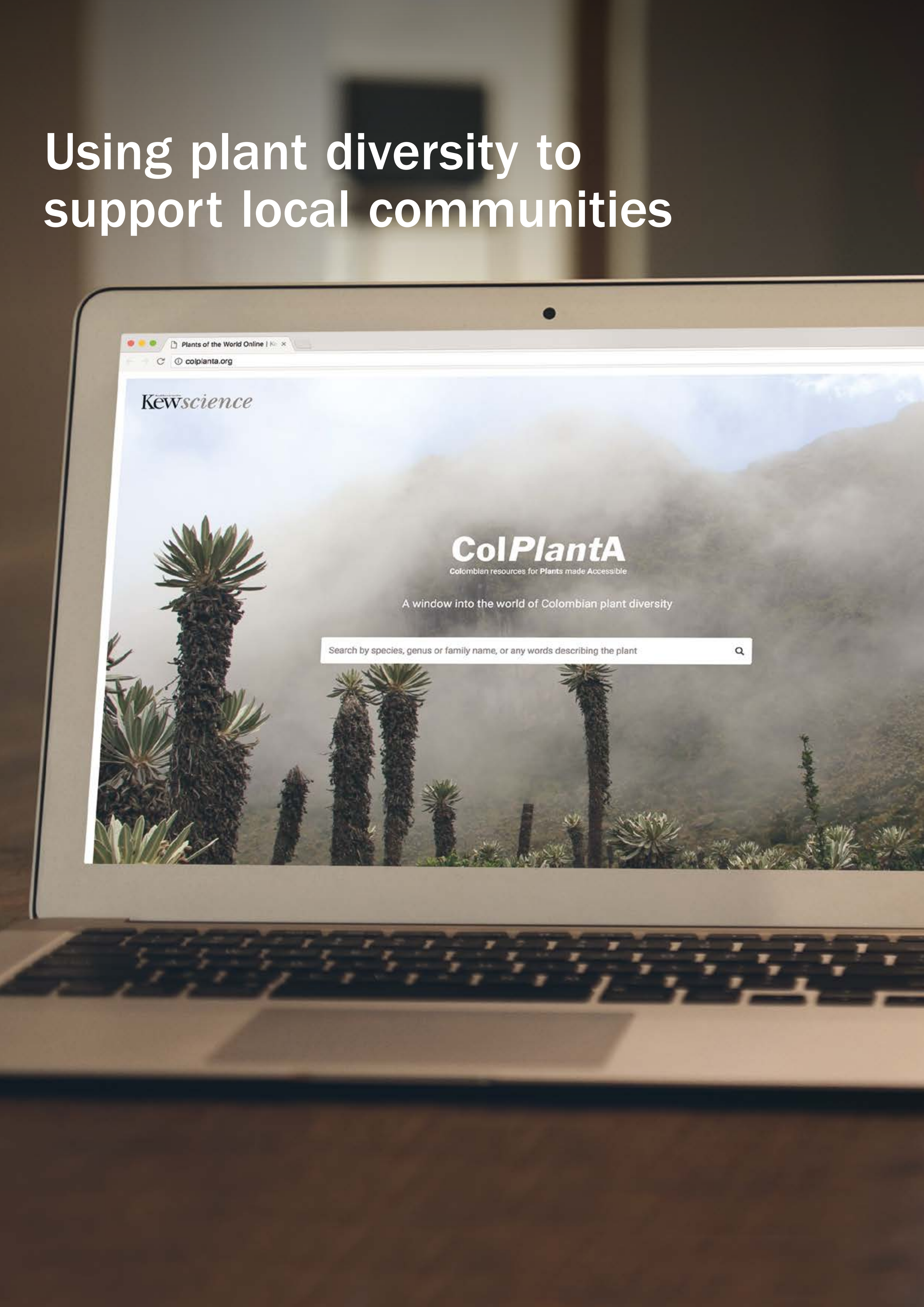
Our research has established herbarium specimens as vital resources for Red List assessment and has transformed Red Listing methods for plants.

Plant uses

Using plant diversity to support local communities



Summary

Research by Kew's Diversity and Livelihoods group improves people's livelihoods and wellbeing worldwide. We do this by conserving plant diversity and supporting sustainable subsistence and income generation in rural communities. We are developing a model for large-scale natural capital restoration, implemented by the Food and Agriculture Organization, and we maximise nature's contribution to people through sustained agriculture, agroforestry and reforestation. Other projects enable the recovery of indigenous peoples' traditional plant-related knowledge and support developing countries' green growth by contributing to the understanding of their plant diversity and uses. We contribute to the global dataset of useful plants, which informs intergovernmental science policies to tackle global challenges.

The Diversity and Livelihoods group provides a bridge between applied science and the Sustainable Development Goals (SDGs). From 2012 to 2018, we were involved in 20 projects in 13 countries (with more than 30 collaborations). Some key highlights from selected projects are described below.

The MGU Useful Plants Project

From 2007 to 2017, we enhanced the capacity of local communities in Botswana, Kenya, Mali, South Africa and Mexico to conserve indigenous plants and improve people's livelihoods. Research on the selection of useful plants species, on seed conservation, plant propagation and planting in community gardens helped to generate income at the local level. The results confirmed the importance of applying a 'holistic approach' to address the dual objectives of biodiversity conservation and sustainable development. Impacts included: (i) 357 species safeguarded in seed banks and propagated in 38 rural communities and 39 schools; (ii) seedlings of 267 species planted and maintained in rural communities; (iii) sustainable income-generating opportunities created for 59 useful plants locally; and (iv) school programmes on useful plants established and 33 undergraduate or postgraduate students tutored.

Great Green Wall initiative

The Great Green Wall (GGW) initiative developed a restoration model to deliver environmental and socio-economic benefits. This was done through the selection of well-adapted species and the prevention of desertification and biodiversity loss, while supporting food security and livelihoods. Since 2013, we have applied a participatory approach, working with local communities, national collaborators and the Food and Agriculture Organization (FAO) in the cross-border zone between Mali, Burkina Faso and Niger. The results informed the wider GGW initiative for the Sahara and the Sahel, and the model was also deployed for FAO's Action Against Desertification programme.

In the GGW initiative over 100 village technicians were trained and seeds of 55 woody and herbaceous species were propagated. The plants were used to restore 2,235 hectares of degraded land and to create sustainable income-generating opportunities for up to 32,000 people. Over 1,000,000 seedlings of the selected species were produced in local nurseries. These seedlings were then planted in about 200 experimental plots to see which key species should be used. We established greater capacity at community level for nursery management, tree planting, forest restoration and the setting up of demonstration plots. Our results informed the development of national plans to halt desertification and to reverse land degradation that were based on the use of indigenous species.

The Plant Conservation Centre

From 2014 to 2017 we set up the Plant Conservation Centre (PCC), a large sustainable nursery of native plants in Ica, Peru. It established reforestation corridors for conservation and ecosystem services, and promoted income generation and education within communities and schools. We supported large-scale agriculture through reforestation and enhancement of biodiversity. The PCC is now a going concern: for example, in September 2017 there were 12,000 plants ready for sale, and the centre had orders for 11,000 plants for reforestation and the construction of native hedges.

Global Tree Seed Bank project

Since 2015, as part of the Global Tree Seed Bank project, we have established a conservation programme to preserve the threatened forests of Hispaniola in the Dominican Republic, and conserved and facilitated the identification of key tree species in Mexico.

Hispaniola

We support the National Botanic Garden, Jardín Botánico Nacional of Santo Domingo, in government efforts to restore and recover both protected areas and urban and semi-urban areas.

We established a new seed bank in 2017 and ensured the conservation and propagation of 250 species. To help conserve the threatened forests, we delivered scientific advice, technical training courses and carry out yearly joint expeditions.

Mexico

Working with the Facultad de Estudios Superiores Iztacala, Universidad Nacional Autónoma de México, we compiled the first list of trees of Mexico, documenting their conservation status and distribution. We conserved seeds of over 300 tree species and generated information on seed management to address the National Forestry Commission's reforestation strategy.

Biocultural collections in Brazil

The programme supports indigenous researchers and assists transfer of traditional knowledge to younger generations. Following publication in 2014 of the Yanomami indigenous knowledge of medicinal plants in their own language, the Ye'kuana people are now recording their knowledge before it disappears. Following our training of indigenous ethnobotanical researchers on the upper Rio Negro in 2016, indigenous researchers are continuing to share and collect data on plant use.

Kew–Colombia Bio Programme

Since 2017, we have led the Kew–Colombia Bio Programme and created two digital portals to aid understanding of the potential use of native plants to boost the national bioeconomy. These portals connect to a large audience and are directly linked with Colombia's Development Plan for greening the country's economy. The programme supports UK projects in regions prioritised by the Colombian government, and we coordinate UK funding streams to support understanding of Colombian plant diversity and uses.

Useful Plants and Fungi Initiative

Our group has developed and leads the research of Kew's Useful Plants and Fungi Initiative by gathering, compiling and analysing data on lant uses worldwide. Information is displayed through the Plants of the World Online portal which is aimed at scientists, governmental institutes and NGOs to identify species of benefit to local people and to inform policy makers.

At-a-glance

- **Biodiversity loss and poverty**
  These problems are intricately linked and should be tackled together. Plant threats include: climate change, overexploitation, shortage of water, habitat loss and invasive exotic species. Yet the livelihoods of small-scale farmers depend on biodiversity.
- **Securing improvements**
  The livelihoods of financially poor rural communities can be improved through appropriate biodiversity conservation activities and scientific research carried out within Kew's Diversity and Livelihoods group.
- **The MGU Useful Plants Project**
  We work with partners in Botswana, Kenya, Mali, Mexico and South Africa to conserve and sustainably use indigenous plants which are important to local communities.
- **In southern Peru**
  A project conserves areas of native vegetation, and develops and demonstrates techniques for habitat restoration and regeneration using local species.
- **The Great Green Wall initiative**
  This aims to tackle the damaging impacts of desertification, transcending political borders to create a wall of vegetation across Africa. We work with partners in Burkina Faso, Mali and Niger to create a network of collaborators, including local community groups, NGOs, forestry officials and government officers.

The results confirmed the importance of applying a 'holistic approach' to address the dual objective of biodiversity conservation and sustainable development.

References to the research

This summary was based on an impact paper ‘Improving livelihoods of people based on useful plants’.

www.kew.org. Read & Watch *Linking plant conservation and sustainable development.*

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Safeguarding the future of Arabica coffee

Washing Arabica coffee in south-west Ethiopia

Summary

Arabica coffee (*Coffea arabica*) is a critically important crop species for Ethiopia and worldwide. Our research has been fundamental in understanding the climate change threats and opportunities for this species, particularly in Ethiopia. We have produced: a rigorous assessment of the risks and opportunities for wild and farmed Arabica in Ethiopia; documents and resources for decision makers; and resources and analyses for intervention planning and action. This work has been included in Ethiopian policy documents, used by a broad range of stakeholders, received numerous citations in scientific journals, had substantial media coverage and been included in the UK's 25 Year Environment Plan and UK Climate Services booklet.

Global consumption of coffee has increased significantly over the last decades, with an estimated 500 billion cups consumed each year. Coffee comes from species of the genus *Coffea*, we only use two of these: Arabica coffee (*Coffea arabica*) and robusta (*Coffea canephora*). Arabica accounts for around 65% of global production and robusta 35%. Ethiopia is the world's third largest producer/exporter of Arabica coffee and is home to at least 95% of the genetic resources for the species.

Impact of the research

Increasing public awareness

In 2012 we published our initial assessment of the impact of climate change on indigenous Arabica coffee. It was one of the first scientific publications to engage the public and private sectors substantially on the threat of climate change to an everyday product. A video entitled *The Forgotten Home of Coffee* increased awareness of Ethiopia as the origin of Arabica coffee, its importance for the sustainability of the coffee sector, and the impacts of climate change. *The Coffee Atlas of Ethiopia* has become an indispensable reference book for anyone connected with the Ethiopian coffee sector and landscape, and the first point of contact for linking to primary data and mapping resources for intervention planning and outreach work. Our paper on the high extinction risk for wild coffee species raised substantial global public awareness of the importance of wild coffee species and of the value of crop wild relatives in general. In a related paper, we reported the first ever extinction risk assessment for Arabica coffee and showed that this globally important species is now classified as Endangered, if climate change is factored in.

Included in government policy

Our work has been included in UK government outreach and policy documents and our research on the impact of climate change on indigenous Arabica coffee was incorporated into Ethiopian government documentation at the ministerial level.

Contributing to Sustainable Development Goals

The Darwin Initiative project Mainstreaming Biodiversity Conservation and Climate Resilience at Yayu Biosphere Reserve (Ethiopia) achieved results for nine Sustainable Development Goals. Overall, the project was transformative for the community. High-resolution forest mapping shows almost zero deforestation over the course of the project.

Increasing revenue from coffee in Ethiopia

We estimate that if our work on building climate resilience in the coffee economy in Ethiopia is taken up it would result in an increase in export revenue of at least US$3 billion over the next 20 years, based on achieving just 10% of the total potential (400%) that we identified in our studies. In addition, there would be considerable scope for reforestation, as forest cover is an essential component of the Ethiopian coffee farming system.

Background to the research

Between 2012 and 2019, four projects led our overall research impacts.

Identifying risk and climate change signal

This initial project in 2012 gathered quality field data and ran analyses for the impact of climate change on indigenous Arabica coffee in Ethiopia and South Sudan. Projections were produced for climatic suitability for wild Arabica coffee, using niche models and modelled climate data. A strong climate response signal was identified, resulting in a projection of a substantial negative impact of climate change on wild Arabica coffee.

Elucidating the resiliency benefits of relocation

This project ran from 2013 to 2018 and assessed the risk and opportunity for Ethiopian coffee farming under climate change. The work was based on niche modelling, remote sensing, climate change projections, and rigorous ground truthing. The research paper shows that under a 'no-intervention' scenario, 40–60% of the area current climatically suitable for coffee farming would be lost by 2080. Conversely, under an 'intervention' scenario that enables free movement of coffee areas, a 400% increase in climatically suitable area could be realised. *The Coffee Atlas of Ethiopia* and summary report provide interpretation for policy makers and key resources for other users.

Challenging the principles and outcomes of 'climate smart agriculture'

This follow on project ran from 2015 to 2018. It was a community-level study devised to link the value-chain to livelihood improvement, biodiversity conservation and climate resilience. The project was very successful in improving livelihoods, based on the production of quality coffee compared to coffee of lower grades. We also showed that coffee production areas are compatible with forest preservation, by showing that there have been negligable deforestation in the project area. Our farm research plots showed that climate adaptation measures were successful in terms of improving productivity and buffering adverse climate conditions, but would not ensure long-term climate change resilience. Despite substantial gains in coffee productivity (up to 100%), the costs involved outweighed any gains. This work focused our research towards the coffee plants themselves.

Emphasising the importance of the wild species gene pool for climate resilience

The objectives of this 2017 to 2019 project were to provide IUCN Red List extinction risk assessments for all 124 coffee (*Coffea*) species, to provide a gap-analysis for existing conservation measures; and to produce a crop wild relative priority grouping for coffee. We found at least 60% of all coffee species are threatened with extinction, 45% are not held in any germplasm collection, and 28% are not known to occur in any protected area. Existing conservation measures, including those for key coffee crop wild relatives, are inadequate. Wild coffee species were identified as being extinction sensitive, especially in an era of accelerated climatic change. The study showed that wild coffee species are critical for coffee crop development and particularly for providing climate-resilience options, a notion that has been supported by subsequent research.

At-a-glance

- **Coffee trees**
  Coffee comes from one of two species in the genus *Coffea*: Arabica coffee (*Coffea arabica*) and robusta (*Coffea canephora*).
- **Ethiopia: home of coffee**
  Arabica accounts for around 65% of global production of coffee. Ethiopia is the world's third largest producer of Arabica coffee and is home to at least 95% of the genetic resources for the species.
- **Backbone of the economy**
  Coffee provides more than 25% of Ethiopia's export earnings, around $350 million. Around 25% of the population, some 20 million people, depend directly or indirectly on coffee for its livelihood.
- **Climate change threats**
  Our computer models indicate wild coffee forests would be lost as the result of climate change – we project from 65% to almost 100% loss. Ethiopia coffee production also be severely negatively affected.
- **Why conserve wild coffee?**
  Our extinction risk assessments for all 124 coffee (*Coffea*) species found that at least 60% are threatened with extinction. Wild coffee species are critical for coffee crop development and particularly for providing climate-resilience options.
- **Relocating coffee farms**
  Using modelling and mapping studies for coffee farming, we project where coffee could be grown until 2080 under a changing climate. Our *Coffee Atlas of Ethiopia* provides an easy-to-use summary for decision makers and other stakeholders.

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Acknowledgements

Generously supported by: The Amar-Franses & Foster-Jenkins Trust.

The study showed that wild coffee species are critical for coffee crop development and particularly for providing climate-resilience options.

Conserving yam diversity to enhance food security in Madagascar

Summary

Our main yams project in Madagascar, where yams are an important food, engaged around 15,000 people. Through the project, protein intake of the participants increased by about 20%. Calorific intake overall was flat, albeit it did increase substantially where rainfall was higher and more reliable. Mean annual income per household increased from 464,300 Ariary per year (around £110 per year or 30 pence per day) to 537,600 Ariary (around £135 per year or 37 pence per day). The project developed a national strategy for wild yams that will provide an evidence base to guide the resilient use of yams in Madagascar for decades via government action. Associated projects are enhancing and embedding these impacts, and enabling them to be realised throughout Madagascar.

In Madagascar, yams are an important food, especially in the late dry season 'hungry gap', when other foods like rice have been used up. Although cultivated varieties are available, much of the rural community opt for eating wild yams. Rural families will harvest their own, while more urban communities may buy locally-sourced wild yams.

However, these yams are disappearing, with people reporting that they need to walk further and further to find yams to harvest. Over 30 yam species in Madagascar are only found there and, based on our assessments, many of these are likely to continue to decline if no action is taken.

Impact of the research

Our Darwin Initiative funded project, 'Conserving Madagascar's yams through cultivation for livelihoods and food security', took place from 2015 to 2018. The project was led by Dr Paul Wilkin and Stuart Cable. Seed tubers of winged yam (*Dioscorea alata*) were provided to 60 communities. In return, they cultivated threatened species and monitored their populations. Winged yam is non-native but was cultivated to provide rapid income and nutritional improvements. The communities were located in northern and south-eastern Madagascar in areas with different levels of use and diversity of wild yams. In all, 3,209 people were trained (47% female) in yam propagation, cultivation, harvesting and wild population surveying.

Nutrition

The project worked with just under 3,000 households in 60 communities, which were divided into three districts (a total of about 15, 000 people). Household calorific intake in the participating communities increased by 28% in the first district, but reduced by 22% in the second district (because of poor early season rains in 2016 to 2017) and by 5% in the third. Thus, overall calorific intake across the project was flat, although it increased substantially where rainfall was higher and more reliable. By contrast, protein intake increased by 24% and 54% in districts one and three, with a decrease of 16% in district two (again owing to climatic conditions). Hence, protein intake increased across the project as a whole by about 20%. In summary, where climatic factors do not limit, cultivating wild yams offers a model system to promote food security and livelihoods across Madagascar.

Income

Mean annual income per household increased from a baseline of 464,300 Ariary (about £110 per year or 30 pence per day) to 537,600 Ariary (about £135 or 37 pence per day) over three years. Thus, over 2,941 households and the three-year duration of the project, we estimate that income was increased by 215,575, 300 Ariary (or about £54,000) for about 15,000 people.

National strategy

The project developed a national strategy for wild yams, coauthored by the project manager in Madagascar and an external expert, Professor Vololoniaina Jeannoda. The methods for the use and conservation of yams described in the strategy are already being used in Madagascar, and villages outside project areas have picked them up from project communities.

Additional impacts

The early successes of the project enabled further fundraising to employ the project's methods with communities in north-western and western Madagascar from 2017 to 2020. This has increased the range of ecological conditions and cultural diversity in which the project demonstrably succeeds. It has also brought a further 33 communities (1,457 households or about 7,300 people) into the project, and at least 4,500 people on the fringes of the project will benefit.

We have funding for the project 'Sustainable yam markets for conservation and food security in Madagascar' from 2018 to 2020. This project aims to protect and enhance the conservation successes of the main project by improving food security, nutrition and livelihoods. This will be achieved by providing business models at multiple scales, sustainable value chains, markets for processed tubers, and nutritional information to guide policy. The aim is that increased income from yam cultivation will underpin long-term, sustainable conservation gains without further international funding.

It is clear from the information presented above, and from interactions with the project teams and communities, that the project has already enhanced lives and livelihoods beyond the 15,000 people who were directly involved. Indeed, we have been told that lives have been saved by the additional income and food security that these Madagascar yam projects have generated.

Background to the research

The 2015 to 2018 project 'Conserving Madagascar's yams through cultivation for livelihoods and food security' was underpinned by over a decade of research in Madagascar on yam (*Dioscorea*) systematics.

Project conservation outputs included multiple accessions of 23 *Dioscorea* species (out of c. 45) as seed, including all of the threatened and economically important wild species found within the project districts. Living germplasm collection was similarly successful, and included 12 of the 18 threatened species. We published 29 IUCN Red List assessments of wild yams species.

Project communication to enhance knowledge of Madagascar's yams, their diversity, use, conservation and food security potential took place through media including radio, TV, blogs, tweets, a website, distribution of T-shirts and annual regional yam festivals.

At-a-glance

- **Boiled yams**
  In Madagascar this food provides carbohydrates, fibre, potassium and a range of micronutrients. While cultivated varieties are available, much of the rural community opt for eating wild yams, an important food especially in the late dry season.
- **Wild ones in decline**
  The wild yams are disappearing. Over 30 yam species in Madagascar are only found there so urgent action is required to halt their decline.
- **In southern Africa**
  Wild yams here aren't often used as agricultural food crops, instead they are important for their unusual species and distinct evolutionary lineage. The risk of extinction in southern Africa is even greater than in Madagascar; 44% are at risk of extinction, mostly due to habitat decline.
- **Conservation**
  Now we know the risks to both southern African and Malagasy yams, it is important we conserve these plants for future generations.
- **Practical projects**
  We support 85 separate Malagasy rural communities to cultivate edible and threatened wild yam species as crops, alongside conserving them in living collections and seed banks.

References to the research

This summary was based on an impact paper 'Yams in Madagascar: biodiversity and its conservation underpinning enhanced food security and income'.

www.kew.org Read & Watch *Tubers in trouble*

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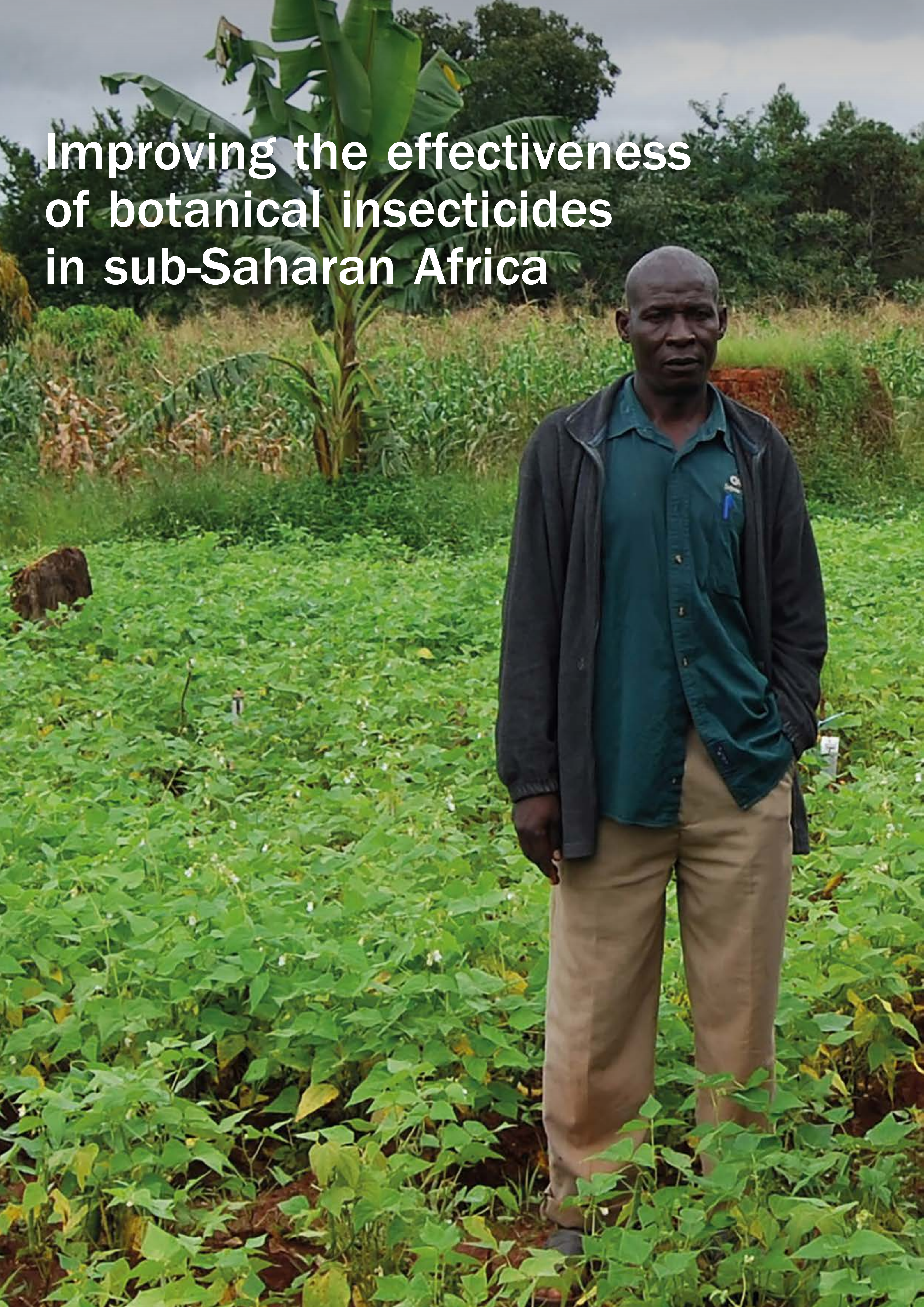
Lives have been saved by the additional income and food security that these Madagascar yam projects have generated.

Improving the effectiveness of botanical insecticides in sub-Saharan Africa



Summary

Smallholders produce around 80% of the world's food but rely on traditional methods of pest management, including pesticidal plants (botanical insecticides). Some of these plants are effective, but others are not, or they might be used or harvested inefficiently or unsustainably. Smallholders in sub-Saharan Africa use botanical insecticides but their use has been hampered by poor basic knowledge, a lack of underpinning science and ineffective applications. Over ten years, a consortium of researchers in the UK and Africa has undertaken research and development that has had a beneficial impact on thousands of farmers in Kenya, Tanzania, Malawi, and Zimbabwe. These farmers are now using these botanicals effectively to control field and storage pests.

Millions of people across the world lead a subsistence lifestyle and grow their food on 500 million or so smallholder farms. These provide employment for around one in four people on the planet and produce 80% of all food in developing countries. The majority of farming in sub-Saharan Africa is carried out on smallholdings, often of less than one hectare. This size limits what farmers can produce, resulting in a precarious existence with problems such as inadequate water, insect pests and diseases. The impact of our research into botanical pesticides for the farmers and the environment of their smallholdings is summarised below.

Impact of the research

Training farmers

We have undertaken more than 20 major training activities, working directly with farmers in countries including Ghana (for Mali and West Africa), Kenya, Tanzania, Malawi, Zimbabwe and Zambia. Training farmers in Kenya and Tanzania, for example, led to more than 4,000 farmers propagating pesticidal plants for home use and more than 40,000 pesticidal shrubs being planted for home use and sale. These farmers have generated new income by growing and selling pesticidal plants. We have shown that pesticidal plants are an economically viable alternative to synthetic pesticides.

Sustainable benefits

Pesticidal plants support beneficial insects in the natural landscapes adjacent to farmland while at the same time having some control of pests. We worked directly with 400 farmers in Tanzania and 236 in Malawi, as well as a further 135 farmers. Their incomes increased by over 13% over the project time frame due to improved use of field-margin plants as botanical insecticides and to support beneficial arthropods, natural enemies of pests. The propagation or management of field margins to allow pesticidal plants to flourish supports pollination and natural pest regulation. These studies provide strong evidence that pesticidal plants are a sustainable alternative to synthetic pesticides.

Commercial development

A botanical insecticide manufacturer in the UK and Rwanda (AgroPy Ltd) is establishing the commercial production of pesticidal plants, specifically Pyrethrum. Our research has informed this effort and we are now researching the commercial development of new biopesticides. We have improved local capacity by establishing a dedicated chemical laboratory in Malawi that now provides chemotype materials across East Africa and ensures the best provenances are used and propagated.

Founding of a research network

We established the first pan-African network of research into pesticidal plants and have hosted two international conferences that were attended by over 250 people from more than 20 countries. The resulting International Society of Pesticidal Plants is a network for researchers to continue to meet, undertake research and drive the adoption and uptake of pesticidal plants for pest control.

Background to the research

Smallholders produce approximately 80% of the world's food but rely on traditional methods of pest management, including pesticidal plants (botanical insecticides). Some of these plants are effective, but others are not and may exacerbate the challenge or might be used or harvested inefficiently or unsustainably. Some are even harmful and should be avoided: natural does not mean safe.

Our underpinning research involves:

- Validating pesticidal plant efficacy through laboratory and field trials, and through determination of the most effective species for pest control from those identified in our region-wide farmer surveys.
- Determining the biologically active plant chemicals in key species including *Tephrosia vogelii, Tithonia diversifolia, Vernonia amygdalina* and *Zanha africana.* Importantly, this research identified significant underlying variation and chemotypes within genera, highlighting the importance of selecting the most effective provenances for propagation.
- Developing approaches for optimising harvesting that are reported in full in our handbook of pesticidal plants. Water is the only extraction medium available to farmers, so methods that use detergents at the extraction stage have been developed. Subsequent field trials have demonstrated that the use of these detergents delivers more effective pest control.
- Developing propagation methods and practical information tailored to farmers needs. The pesticidal plants that are included benefit home production, thereby reducing unsustainable wild harvesting, and support populations of beneficial arthropods when planted in field margins.
- Demonstrating the economic viability of pesticidal plants when compared to synthetics.
- Showing that the impact of pesticidal plants on beneficial arthropods (natural enemies of pests) and pollinators is significantly lower than that of synthetic pesticides.
- Developing Farmer Research Networks for mass uptake and training.

At-a-glance

- **Using plants to control pests**
  We help farmers on smallholdings in sub-Saharan Africa fight back against insect pests by researching the pesticidal properties of plants. These can make botanical pesticides, an alternative to commercial pesticides.
- **A natural defence**
  Many plants protect themselves against insects by producing their own chemical defences that are toxic or repellent. For example, we found that sweet potato, *Ipomoea batatas*, an important staple food in Uganda, produces natural defences in this way. We have investigated many more such plants.
- **Environmental benefits**
  Most botanical insecticides are as effective at controlling pests as synthetic products but are much less harmful to beneficial insects such as ladybirds, spiders and wasps and help to control aphids and caterpillar pests.
- **Cheap and locally-grown**
  Another advantage of pesticidal plants is that they are cheap to grow and can often be harvested by farmers themselves. All in all, plants are a compelling alternative to synthetic pesticides.

The propagation or management of field margins to allow pesticidal plants to flourish supports pollination and natural pest regulation.

References to the research

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www.kew.org Read & Watch *Using pesticidal plants for crop protection.*

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Policy and regulation

An authoritative plant names service for the health-care industry

Herbal medicines on sale in South Korea

Summary

Kew's Medicinal Plant Names Services (MPNS) enhances the safe use of plant-derived health products globally. We achieve this by tackling the ambiguity and inconsistency found in how health regulations, patient records and quality control procedures refer to plants. Our website permits searches of the common, pharmaceutical and scientific names used for plants and herbal drugs in global trade and regulation: over half a million names for around 28,000 plants. We have corrected and enriched the names used by many health regulators internationally to improve efficiency and effectiveness of regulation. Working with regulators, we also developed an ISO standard for medicinal products to facilitate communication. Other tools ensure that published natural-product research is both meaningful and discoverable.

Millions of people, typically in rural parts of the United Nation's Least Developed Countries, rely on plant-based remedies for their primary health care, being unable to access or afford pharmaceutical drugs. Governments and the World Health Organization (WHO) promote herbal remedies alongside conventional medicines for treating chronic conditions and to reduce costs. Increasingly, consumers seek 'natural' remedies with 90% of Germans having used herbal products. The herbals market is projected to reach US$117 billion by 2024.

However, enormous confusion exists regarding exactly which plants are being used, regulated and prescribed. Specific products are marketed under multiple drug names, while one name can refer to drugs derived from many different species. For example, 'ginseng' products are derived from any of 16 species with differing chemistry. Regulation, quality-control, trade and prescription are therefore compromised with significant and well-documented health risks to consumers.

Impact of the research

Since 2014, the MPNS has brought about significant improvements in how safely herbal products are regulated and used. Our initial research confirmed that regulation of natural products is highly complex. Achieving meaningful change required interventions with diverse actors including regulators, pharmacopoeias (the primary source of names for regulators) and the pharmacists and academics writing those pharmacopoeias. We needed both to improve the consistency and precision of their data and to bring about procedural change.

Our primary interventions and impacts have been:

Enhanced effectiveness for individual regulators

To date, our validation service has been used by 12 major health agencies in the US, EU and WHO. Collaborating scientists from a further eight institutions have used the MPNS to improve their data and publications. Regulators have achieved significant efficiencies by avoiding having to check and curate plant names, but more importantly individual agencies can be confident of their own data integrity: avoiding poor decision-making, ambiguous regulations or meaningless records. We also expanded their access to databases and literature using alternative names.

Facilitating information sharing among regulators

We are contributing to more consistent health regulations and more effective communication between regulators. Our services enable all players to comprehensively locate relevant research, clinical trials, patient adverse reactions or drug interaction reports. Potentially our most significant long-term impact will be through implementation of a new ISO Standard for Medicinal Products facilitating further improvements among regulators worldwide.

More effective pharmacovigilance

We work closely with the WHO's Uppsala Monitoring Centre (UMC). UMC supports the national pharmacovigilance centres of 134 member states and is responsible for global surveillance of medicinal products, including herbals. The MPNS ensures the integrity of UMC's systems and has enhanced their ability to detect adverse reactions to herbal products reported by national centres using different names.

Promoting best practice among health professionals

We have run 12 training workshops for over 300 health professionals at events across seven EU countries. These workshops have increased awareness around why scientific names are needed, obstacles regarding their use, reference resources and best practice. Bob Allkin has contributed regularly to the WHO's training of pharmacovigilance professionals. Our newsletter, with 720 subscribers, discusses relevant issues and publicises guidelines.

Enhanced quality of names in published research

Editors of many natural-products journals now recommend or require that authors submitting manuscripts use the MPNS to check plant names. The *Journal of Integrative Medicine* dedicated an editorial to our best-practice guidelines and the Society for Economic Botany cite the MPNS as their preferred source for plant nomenclature.

Facilitating medicinal plant research

How many medicinal plants? Where are they used? In what families? Such basic questions cannot be answered without a reliable, comprehensive species list. Previous lists were local or included species multiple times under different synonyms. The MPNS is unique in being globally comprehensive for plants in regulation or trade and in embedding full synonymy (scientific and pharmaceutical). We continue to add plants recorded in ethnobotanical literature. The MPNS is a powerful research tool permitting many new analyses, including an ongoing phylogenetic analysis and geographical comparison of where plants are used and where they are from.

Facilitation of conservation

How can conservation efforts be effectively prioritised without clarity as to which species are threatened? The IUCN's medicinal plant specialist group previously listed 27,000 plants as medicinal until our analysis reduced this to c.18,000 unique species, with 9,000 names being synonyms. The MPNS supports the IUCN and has since expanded their list to 28,000 genuine species with documented medicinal use. CITES recently adopted the MPNS as part of their strategy for the Regulation of Trade in Medicinal Plants.

At-a-glance

- **One plant, many names**
  There are 1.6 million published scientific plant names but only an estimated 350,000 plant species, so the potential for confusion is clear.
- **Medicinal plants**
  A single name such as 'ginseng' can be used for more than one plant. Using the wrong plant in a herbal preparation can have adverse health effects and even cause death.
- **Trusted resource**
  The MPNS builds upon Kew's existing taxonomic resources and enriches these with plant and herbal drug names as they are used within legislation and medicinal literature.
- **How big is it?**
  The MPNS resource covers approximately 28,000 species corresponding to c.32,800 scientific names used in the literature. It links these to 104,000 non-scientific names from the same literature, and to over 200,000 scientific synonyms in Kew's taxonomic databases.
- **Using the MPNS**
  Our portal provides access to medicinal plant data and medicinal literature citations using any pharmaceutical, drug, common or scientific plant name. We offer various other services to organisations who have plant lists or databases they would like to validate or harmonise, as well as offering consultancy and training.

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Acknowledgements

The MPNS acknowledges support from the Wellcome Trust, The Charles Wolfson Charitable Trust and the Uppsala Monitoring Centre.

The MPNS is unique in being comprehensive for plants in global regulation or trade and in encompassing all scientific, pharmaceutical and common names (in multiple languages and scripts).

Protecting endangered wild plants from international trade

Summary

The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) is an international agreement that aims to regulate and monitor trade in endangered wild plants and animals that are considered threatened through trade. There are over 30,000 plant species listed in CITES Appendices. CITES entered into force in 1975 and, to date, 183 countries are Party to it. The UK has been a Party since 1976 and Kew is the UK's Scientific Authority for plants. We play a major role in supporting and guiding the development of CITES regulations and resources. For example, we provide scientific advice for licensing activities, review proposals to amend CITES Appendices and create checklists and resources.

Kew is a global leader in botanical knowledge, research and conservation. As such, we play a major role in the development and implementation of CITES regulations.

How we support CITES

Checklists and user guides

We developed nine checklists which have been incorporated into the national legislation of countries such as Thailand, Gabon, Madagascar and Georgia. Checklists and user guides first published by Kew have since been accepted by CITES as the standard user guides and information documents. We had a major role in developing non-detriment finding assessments for CITES and codeveloping the current CITES document for perennial plants. This is the standard methodology for assessing whether a species is threatened by trade, used by scientific authorities around the world and has been used in training workshops in Vietnam, Peru, Georgia and China.

Reviewing proposals

We review data and potential listings for the EU Scientific Review Group and the CITES Conference of the Parties, providing comprehensive briefs and analyses for the UK government that are viewed as giving direction to the Parties. Kew analyses and reviews EU-commissioned assessments on CITES-listed plants, helping the EU to develop new regulations.

Kew led the CITES Plants Committee and Nomenclature Working Group, impacting critical conservation issues. On behalf of the EU Commission, our scientists have attended high-profile EU missions to CITES countries to conduct conservation and trade assessments (Mexico) and have provided capacity building in Uganda and Madagascar.

Training

We train Border Force and police forces throughout the UK through its Wildlife Foundation Course (which runs three times each year) and have run a seminar to train Wildlife Inspectors on CITES requirements. Our training materials on the international enforcement of CITES have been sent to France, Chile and Madagascar. We train students and Kew staff in CITES.

Technical support for enforcement

Our timber anatomy laboratory is highly regarded, and specimens of seized timber products are sent to it from all corners of the globe. We provide technical support through DNA and analytical work, and formed the baseline for an international investigation into illegal timber trade in the EU with US partners. We are regularly called on to consult with the EU Enforcement Working Group, Europol, and Interpol regarding the illegal trafficking of plant specimens. Enforcement agencies regularly require Kew to identify seized plant material and then to testify when offenders are prosecuted. Kew Gardens' quarantine house keeps seized plant materials until a ruling is made.

Increasing awareness

By holding regular meetings with traders (CITES Sustainable Users Group), we improve awareness of CITES requirements. This reduces wildlife crime by facilitating informed enforcement and improved awareness through consulting with and providing guidance to international organisations.

Providing advice

We meet with UK MPs to discuss CITES and complex conservation systems, addressing the challenges facing the long-term conservation of plants through multidisciplinary contributions from scientists, government and stakeholders. Our advice and support led to funding from the UK government's Illegal Wildlife Trade (IWT) fund (£13 million over four years) for the first time in 2018. We participated in the IWT Conference to showcase CITES-listed plants, the first time plants were featured, raising the awareness of illegal trade in plants internationally.

Background to the research

The EU is also a Party to CITES, which it implements through the EU Wildlife Trade Regulations (EUWTR). Kew input into the development of these regulations, which are stricter than normal CITES regulations and came into force in 1997. In 2018, we assisted the UK government in transferring the EUWTR into UK law in preparation for the UK's exit from the EU.

CITES and the EUWTR form the basis for the work done by the Kew CITES team. The UK, with advice from the Kew CITES team, is working with the CITES Secretariat to achieve compliance under the National Legislation Project for its overseas territories.

Our CITES team performs instrumental work in capacity building, artificial propagation, plant trade issues, sustainable use, taxonomy and nomenclature, horticulture, wood anatomy, and DNA techniques. We coordinated the production of the first CITES references for plants; these have been adopted as standard references by the Conference of the Parties to CITES. To date, Kew has published six volumes on orchids (1995–2009), bulb plants (1999), cacti (1992, second edition 2016), *Aloe* and *Pachypodium* (2001), succulents (1992) and carnivorous plants (2001). In addition, we have also published CITES user's guidance for cacti (2012), cycads (2013) and timber (2015). We have influenced the development of non-detriment finding procedures for perennial plants and timber species.

Representatives from Kew, in its capacity as the UK Scientific Authority for plants for CITES, have attended Standing Committee meetings (2012, 2013, 2014, 2016 and 2017), the CITES Plants Committee (2012, 2013, 2014, 2015, 2017 and 2018) and the Conference of the Parties in 2013 and 2016. Our scientists have also served on CITES scientific committees and we attend or advise regular meetings of CITES and various EU Committees, providing guidance and support to inform the CITES decision-making process.

At-a-glance

- **What is it?**
  CITES is an international agreement between governments. It aims to ensure that international trade does not threaten the survival of plants and animals that are traded.

- **How does it work?**
  Every three years the countries (or Parties to the Convention) meet to add, delete or amend species listings on the CITES Appendices. CITES regulates the trade in endangered plant species under three Appendices, and species must meet certain biological and trade criteria in order to be listed. Over 30,000 plant species are protected by CITES.

- **What is the impact?**
  This is difficult to fully assess globally but for a snapshot of trade in illegal plants in the UK we obtained data of plant seizures in 2016 by the UK Border Force at Heathrow Airport. This revealed that 220 individual CITES-related plant seizures were made.

- **Illegally traded plants**
  Live orchids dominate seizures, followed by plants used in traditional medicines and health care products. This pattern is similar to other studies, indicating that the illegal trade in plants globally is dominated by orchids.

Enforcement agencies regularly require Kew to identify seized plant material and then to testify when offenders are prosecuted.

References to the research

This summary was based on an impact paper 'Kew's role as CITES Scientific Authority for the UK'.

Many of the CITES resources we have published are available online at **www.kew.org**.

CITES and EU Information. www.cites.org/ and http://ec.europa.eu/environment/cites/home_en.htm.

The EU-TWIX database assists national enforcement agencies, including CITES Management Authorities, in their task of detecting and monitoring illegal trade in wild plants and animals covered by the EUWTR. www.eu-twix.org/. Resolution Conf.12.11 (Rev CoP17). Standard Nomenclature. https://www.cites.org/sites/default/files/document/E-Res-12-11-R17.pdf.

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Wild orchids on
a market in China

Authenticating plants and fungi used in commercial products

Aristolochia gigantea

Summary

Kew's Commercial Phytochemistry Unit helps regulatory and commercial bodies authenticate plant and fungal extracts that enter trade, using our knowledge about the distribution of natural products and the pharmacology and ecological role of these compounds. We have helped develop robust analytical methods to identify species. However, these methods have limitations and it is sometimes necessary to incorporate other approaches, such as DNA bar coding, to assist in differentiating species. Our ability to do this research relies on access to verified material from different provenances and on our network of collaborators who can supply verified samples.

Our research on the authentication of plant and fungal extracts entering into trade has increased supplier and producer awareness of issues associated with the quality of materials. We have shown how products can be compromised by the use of adulterants and substitutes.

We have investigated the chemistry and/or biological activity of about 24,000 species. These projects use our taxonomically curated collections and the expertise of our scientific staff (in systematics, chemistry, anatomy and taxonomy) in the development of analytical methods. We also highlight the importance of developing DNA-based techniques to assist in the identification of plants when chemical techniques are not robust enough.

Impact of the research

The following examples illustrate the impact we have had on natural product authentication.

Human safety: food

We assist the Border Force in dealing with adulterated plant material; for example, differentiating Chinese star anise from the toxic Japanese star anise. In July 2016, we were asked to assist with the analysis of samples from a young girl who died after eating a baguette from Pret a Manger. In this case, we provided authoritative data to authenticate the presence of compounds from sesame seed that were traceable to the baguettes. Our knowledge about the distribution of toxic compounds has also enabled us to identify species that should not be used in foods.

Human safety: medicinal plants

Species of *Aristolochia* contain artistolochic acids (AAs) which are associated with renal failure. Drugs used in traditional Chinese medicine as well as slimming treatments were found to contain AAs and were associated with 14 cases of renal failure and two deaths in the UK. We developed a sensitive analytical method to detect these AAs that was used to support convictions. Further work evaluated the diversity of species containing AAs and showed that the toxicity of *Aristolochia* cannot be attributed to AAs alone.

Trade of endangered plants

We have provided scientific evidence to support enforcement officers in seizing CITES-listed plant products and in prosecuting those who trade in them. We have also assisted suppliers in checking material, the most frequent enquiry is associated with species of ginseng, which can be differentiated by their ginsenosides.

Poisoning

Police contact us to help with investigations that involve human and animal deaths, especially if they could involve unusual plant toxins. Our knowledge and our analytical equipment enables us to identify and detect very small amounts of toxins.

Improving trade monographs

Through our work with suppliers and regulatory authorities, we help to improve detection criteria and to increase the number of species covered by official trade monographs.

Authentication of plants used in cosmetics

We worked with Boots to review the quality of and supply chain for all the plant extracts in their Botanics range. The results supported a system to evaluate the sustainability of the products. In work with Procter and Gamble, we selected plants and then evaluated and characterised the metabolites in plant extracts to be used in hair and skin products.

Background to the research

In the late 1960s, we became involved in different aspects of plant and fungal chemistry. Initially the emphasis was on food chemistry, but as natural-product techniques improved, we concentrated on chemosystematics, gathering data about the distribution of certain compounds in plants.

In the late 1980s, we received funding for drug-discovery projects such as antimalarials, drugs affecting the central nervous system, antimicrobials, potential HIV medicines and pest controls. These projects were supported by appropriate analytical methodologies, such as nuclear magnetic resonance

(NMR) and mass spectrometry (GC-MS/LC-MS), and these resources have been maintained. This work increased our understanding of the pharmacological and ecological roles of many compounds. We established our chemical mass spectral and biological activity libraries, which underpin our current authentication projects.

The 1990s saw a move away from natural products to computational chemistry. Meanwhile, we were increasingly being asked to authenticate or evaluate the quality of traded plant-derived materials, as well as the chemistry of plants involved in drug–herb interactions, especially those associated with traditional Chinese medicine. We built up a taxonomically verified collection, the Chinese Medicinal Authentication collection, which enabled us to develop analytical methods for the detection of, for example, toxins in *Aristolochia* and *Asarum*.

In 2003, Boots asked us to evaluate samples of sandalwood, and issues were identified in all 29 of the main suppliers. We then reviewed all of the botanical extracts in their Botanics range of cosmetics, which led to Kew's first science-led trade mark license agreement. We also worked with Procter and Gamble to look for new leads, and to authenticate material entering the trade for their Olay range and medicinal products. Similar work on natural product authentication was conducted with several other companies. Our chemosystematic knowledge enabled us to assist with enquiries associated with the trade of endangered species and with unusual toxins in criminal cases.

In 2017, Procter and Gamble negotiated a new grant that utilises our natural product knowledge in cosmetics, detergents and medicinal products. This is in addition to a new trade mark license that involves the identification and authentication of plants. The Commercial Phytochemistry Unit was created to help facilitate this project and requests to authenticate plants in the trade.

At-a-glance

- **What does the Commercial Phytochemistry Unit do?**
  We evaluate functional and novel foods, drinks, dyes, fragrances and medicinal plants. We bioprospect for active compounds for drug development, with a focus on insect control, antimicrobial and immunomodulatory activity.
- **Who uses it?**
  We work with industries, regulators and research institutes worldwide to scientifically characterise the uses of plants and fungi, or authenticate and identify the plant and fungal origins of extracts entering the trade.
- **Food safety**
  We assist the Border Force in dealing with adulterated plant material: for example, differentiating Chinese star anise from the toxic Japanese star anise. We identify species that should not be used in foods.
- **Other poisons**
  Our chemical analytical methods can detect harmful plant toxins in herbal preparations and in cases of deliberate poisoning.
- **Plant conservation**
  We provide scientific evidence to support enforcement officers in seizing CITES-listed plant products and in prosecuting those who trade in them.
- **Natural cosmetics**
  We select plants and evaluate them by analysing their metabolites, to find plant extracts for cosmetic and other uses.

References to the research

This summary was based on an impact paper 'Authentication of plants entering the trade and used in crime'.

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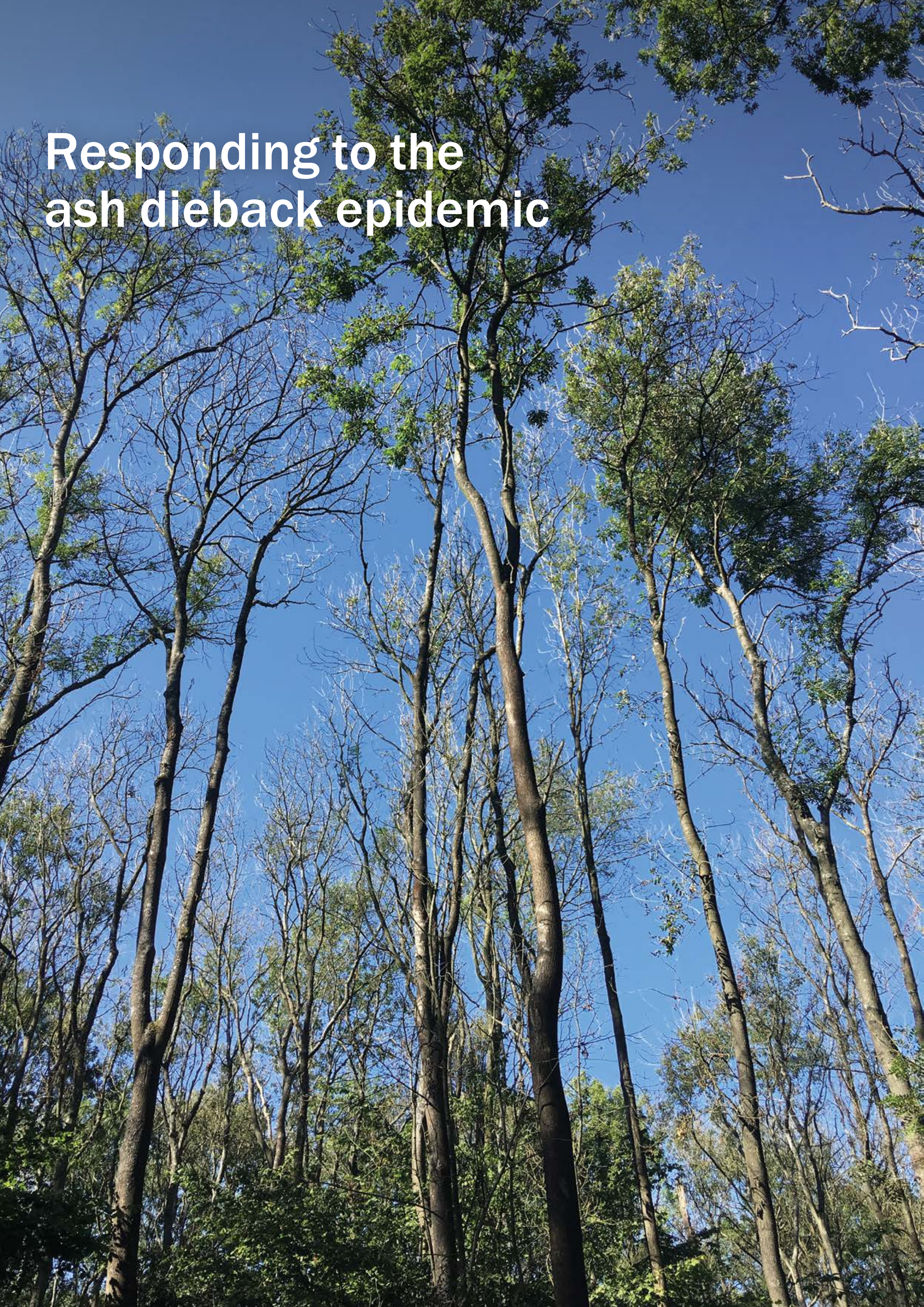
Our knowledge and our analytical equipment enables us to identify and detect very small amounts of toxins.

Responding to the ash dieback epidemic



Summary

Our research has provided evidence that has helped the Department for the Environment, Food and Rural Affairs (Defra) to manage and respond to ash dieback in the UK. The research has helped stakeholders understand: the proportion of ash trees that can be expected to die in the UK because of ash dieback, and the speed at which they are likely to die; the genetic basis of resistance to ash dieback; the viability of breeding to increase ash dieback resistance and the effectiveness of natural selection in evolving increased ash dieback resistance; the susceptibility of ash trees to emerald ash borer; and the diversity of genes in the fungus causing ash dieback.

Fungal diseases can cause huge and irreparable changes to natural habitats. One such disease is ash dieback, caused by the ascomycete fungus *Hymenoscyphus fraxineus*, a pathogen of Asian origin. The disease threatens to dramatically change woodland and environmental landscapes in the UK and across Europe. Ash dieback was first found in native woodlands in Britain in 2012, causing an immediate ban on the movement of ash. Since then, research by our Plant Health team has provided stakeholders with information to respond to the threat.

Impact of the research

Public awareness

Our research was widely reported by national and international media. It was covered by the BBC News website, BBC Radio 4's Six O'Clock News, the *Financial Times*, *The Guardian*, *El Mundo* (Spain), *Daily Express* and *Daily Mail*.

Kew's senior research leader in Plant Health, Professor Buggs, has spoken at many meetings for stakeholders, including: The Future for English Woodlands conference at The National Memorial Arboretum, Staffordshire, 30 October 2018; Plant Health Conference organised by The Earth Trust, Oxfordshire, 17 October 2018; South-East & London Tree Health Event 2018 organised by the Forestry Commission, 12 February 2018; and a dissemination event for the Tree Health and Plant Biosecurity Initiative, held in London, 7 February 2018.

Policy work

Our research has informed Defra policy on ash dieback, with the major focus being on breeding UK trees for resistance and enhancement of natural selection. In 2019, Defra published an ash evidence strategy document that was partly based on this research.

Richard Buggs presented our work at the Science for Defra conference on 29 March 2017. One of his papers was cited seven times the 2019 National Academies of Sciences, Engineering and Medicines report *Forest Health and Biotechnology: Possibilities and Considerations*. It contributed to three recommendations of the report.

Richard Buggs was a member of the management committee of the European Cooperation in Science and Technology (eCOST) action group '*Fraxinus* dieback in Europe: elaborating guidelines and strategies for sustainable management' (FRAXBACK). This ran from 2012 to 2016, and resulted in the 2017 publication *Dieback of European Ash (*Fraxinus *spp.) – Consequences and Guidelines for Sustainable Management* (SLU Press, Uppsala, Sweden). Our ash genomics research informed and contributed to this action.

Dr Maryam Rafiqi, an early career research fellow in Plant Health, showed that effector gene diversity in *Hymenoscyphus fraxineus* is low in European populations of this fungus when compared to the diversity in populations from across the native Asian range of the species. Therefore, every effort should be made to prevent further genotypes of the fungus entering Europe. This policy has been adopted by Defra.

Background to the research

An in-field assessment of the damage caused by ash dieback in the UK, carried out across field research sites in the autumn of 2016, and a 2018 meta-analysis of studies in Europe provided information about the proportion of ash trees that can be expected to die in the UK as the result of ash dieback, as well as information about the speed at which they are likely to die. This work was led by Richard Buggs, in collaboration with Forest Research and Queen Mary University of London (QMUL).

We have investigated the genetic basis of resistance to ash dieback. A paper led by Richard Buggs and published in *Nature* reported the genome sequence of European ash. The genome assembly led to the discovery of genetic markers associated with ash dieback resistance by association transcriptomics. Kew/QMUL PhD student Jonathan Stocks discovered markers for ash dieback resistance using a genome-wide association study of the Forest Research field trials.

The genomic data for ash provided by our research group and other collaborators, alongside reviews of relevant literature, have shown that a breeding programme for resistance to ash dieback is viable and could be accelerated using genomic information. This information also suggests that natural selection may be effective in evolving increased resistance to ash dieback.

Our Plant Health team has also collaborated with researchers at Ohio State University, the John Innes Centre, and NIAB EMR to investigate the susceptibility of ash trees to emerald ash borer. This research predicts that European ash may be less susceptible to emerald ash borer than American ash species.

Maryam Rafiqi was second author on a paper published in *Nature Ecology and Evolution* reporting the genome of the ash dieback fungus *Hymenoscyphus fraxineus*. This work was led by the Earlham Institute, and Dr Rafiqi provided analyses of effector genes.

At-a-glance

- **Fungal disease**
  Ash dieback is caused by the ascomycete fungus *Hymenoscyphus fraxineus*, a fungus of Asian origin.
- **Threat to UK woodland**
  Ash dieback will dramatically change woodland and environmental landscapes in the UK and across Europe. Our meta-analysis of reports from Europe, done by Kew scientists, predict that over 60% of ash trees in Britain may die.
- **Ash tree genome**
  We led the sequencing of the ash tree genome and have found variants within it that are associated with resistance to ash dieback in UK populations.
- **Breeding programme**
  Our research suggests that it will be possible to breed ash trees with greater resistance to ash dieback.
- **Fungal genome**
  We have identified elements of the ash dieback fungal genome that contribute to its virulence.

A pathogen of Asian origin, the disease threatens to dramatically change woodland and environmental landscapes in the UK and across Europe.

References to the research

This summary was based on an impact paper ‘Responding to the ash dieback epidemic’.

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Training and public awareness

Training the next generation of plant taxonomists

Summary

Our two short courses, Tropical Plant Identification and Applied Plant Taxonomy, Identification and Field Survey Skills, help address globally recognised skills shortages. The courses are aimed at early career UK and international environmental scientists and PhD students, and are led by Kew staff experienced in managing specialist training. During the review period, we have trained 148 students (90 at Kew and 58 abroad). *The Kew Tropical Plant Identification Handbook* has been published using course content and is a bestseller. The Tropical Plant Identification course runs annually and is oversubscribed each year. Also oversubscribed, the Applied Plant Taxonomy, Identification and Field Survey Skills course has been externally funded by the National Environment Research Council (NERC).

To address the global skills shortage in plant identification and naming, we offer two short courses: Applied Plant Taxonomy, Identification and Field Survey Skills and Tropical Plant Identification. Both courses are designed for individuals working or studying in the environmental sciences sector from postgraduate to professional level, within the UK and overseas. They serve different audiences to the longer-term postgraduate training delivered by our MSc in Plant and Fungal Taxonomy, Diversity and Conservation. *The Kew Tropical Plant Identification Handbook* was developed by the course organisers and teaching staff to act as supporting material. This book extends the global outreach and the plausible impact of Kew's expertise in plant identification.

Impact of the training

The key strength of our courses is the integration of taxonomic and identification skills with fieldwork, taught by experts in their areas using Kew's unrivalled plant collections. By working with a range of plant materials (dried and living), both in the Herbarium and in the field, we ensure that participants learn to apply these skill sets in a range of scenarios. We aim to immerse participants in Kew's dynamic research environment, in which daily use of taxonomic and field skills demonstrates their relevance to careers in the environmental sciences sector.

Applied Plant Taxonomy, Identification and Field Survey Skills

This course gives participants the following key skills. First, to identify 40 key plant families using morphological characters and to transfer identification principles to any taxonomic group in the field, using existing identification tools correctly and efficiently. Then, to apply the principles of plant taxonomy and nomenclature, including a correct interpretation of scientific names and collections. Participants will be equipped to demonstrate an awareness of the role of molecular, phytochemical and anatomical tools in systematics. Also, to select appropriate methodologies, field tools and technologies for field survey work. Finally, to apply taxonomic and field survey data to species conservation assessments. In terms of career development, they will be able to access a wealth of useful contacts for help with complex issues that they may face in the UK environmental sector.

Fifteen participants attended each of the six courses held during the review period, amounting to a total of 90 individuals trained in these skills. These individuals came from 50 institutions, represented 27 nationalities, and varied from PhD students to established researchers. Courses were annually oversubscribed, with an average of 27 applicants for the 15 places available each year.

Tropical Plant Identification

This course gives participants an overview of 70 of the most commonly encountered tropical plant families, as well as an introduction to plant morphology and identification tools. Through short illustrated lectures and extensive hands on practical sessions, our botanists demonstrate the key characters for each family, sharing their expert tips for identification. Attendees join identification sessions focused on different regions in the tropics, and visits to the living collections provide a chance to apply this knowledge 'in the field'. The course also gives participants the opportunity to make connections with experts at Kew and with other course attendees. These relationships often develop into future collaborative projects.

Over the review period, seven courses have been run with 15–16 participants each, amounting to 108 individuals trained. These participants came from 63 institutions, representing 41 nationalities, and their background varied from PhD students to established researchers. The course has been regularly oversubscribed, with 30–40 applicants for the 16 places available each year.

Overseas courses

From 2016 to 2018, we have trained 63 participants (Singapore, 15; Indonesia, 21; Colombia, 27) in country. Being in-country means that participants from smaller resource-poor institutes are likely to be able to attend thanks to reduced travel and subsistence costs.

Successful book

The Kew Tropical Plant Families Identification Handbook, now available in a second, revised edition, is given to all course participants as course material. The first edition sold out (1,802 sold); 2,169 copies of the second edition have sold since its publication in 2016 and a reprint is planned.

Participant feedback

In feedback surveys, the majority of participants chose to rate the courses with the highest rank available. Course contents, course materials, teaching methods, pace of course, precourse information and communication and administration were all rated as either 'Excellent' or 'Good'. Participants found the practical exercises using the plant specimens and resources available at Kew one of the most useful elements.

Additional related training

Plant taxonomy and identification training is offered to our MSc students and to those studying for the Kew Diploma in Horticulture. The latter is a three-year course run by the School of Horticulture, undertaken by approximately 12 horticultural students who are employees of Kew. Several diploma students have gone on to take taxonomy MSc courses, including the Kew MSc. The diploma teaching undertaken by Kew Science is the '*Plant Systematics* module'. This has been an integral part of the course since its inception, and currently comprises 32 hours of teaching run over the spring term (April to June). This diploma teaching is an important collaboration between the Science and Horticulture, Learning and Operations directorates, teaching the principles of plant evolution and diversity to a broad horticultural audience.

Background on the need for training

Identifying species and understanding taxonomic concepts are central competencies in biological science, building the basis for 'conservation literacy'. A dearth of individuals with skills in taxonomy, systematics (including identification), and fieldwork has been documented in several sources, including the 2008 House of Lords Science and Technology Committee follow-up report on Taxonomy and Systematics, the 2011 Ecological Skills report by the Institute of Ecology and Environmental Management, and NERC's 2012 Most Wanted report. A recent example is a 2014 publication on the current status of UK Plant Science by the UK Plant Sciences Federation in which taxonomy, systematics and fieldwork are listed as areas that need improved training to meet a major UK skills shortage. In addition, plant taxonomy was named as an area for which 'employers reported difficulties in hiring scientists with specialist practical expertise'.

At-a-glance

- **Kew-based courses**
  Kew experts teach on a number of postgraduate courses at Kew, using our unrivalled collections to train scientists in essential skills.
- **Tropical Plant Identification**
  This course, which arose from weekly family identification sessions in Kew's Herbarium, has been run regularly since 2004. It is taught by our botanists, who all have in-depth knowledge of tropical plants and habitats. The course is suitable for conservation and environment professionals, graduate students, ethnobotanists, ecologists and zoologists.
- **Plant Taxonomy, Identification and Field Skills**
  Our scientists provide lectures and practical information on the identification of common plant families, field survey and analytical techniques, plant taxonomy and nomenclature, and molecular and anatomical methods in systematics. This course is aimed at PhD students and early career researchers undertaking all aspects of environmental science but particularly ecology, botany and conservation.
- **Other training**
  We work with partner institutes overseas to deliver tailor-made courses. Closer to home, we also contribute to training our MSc course students, horticultural diploma students and staff.

Identifying species and understanding taxonomic concepts are central competencies in biological science.

References to the research

This summary was based on an impact paper ‘Training in plant taxonomy, plant identification and field survey skills’.

Details of how to apply for these courses can be found at **www.kew.org**.

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Utteridge, T. M. A. & Bramley, G. L. C., eds. (2016). *The Kew Tropical Plant Families Identification Handbook*. Revised edition. Kew: Royal Botanic Gardens, Kew.

Funding

We have been awarded five grants from the National Environment Research Council (NERC) to run the Applied Plant Taxonomy, Identification and Field Survey Skills course from 2013 to 2018.

Raising awareness of the diversity, uses and conservation of fungi

Summary

The 2018 report *State of the World's Fungi*, together with the accompanying two-day symposium attended by more than 250 delegates, has highlighted the importance of fungi to audiences far beyond academia. It is estimated that 70% of UK adults saw, read or heard something about the report an average of 5.8 times. Already the report's findings have influenced teaching, public outreach activities and government departments. As awareness of the importance fungi grows, further impacts are predicted.

State of the World's Fungi and the accompanying symposium were global firsts. They received phenomenal social media and press attention that considerably increased the awareness of fungi beyond academia. The global nature of the symposium was shown by the broad diversity of its 263 delegates, who came from 128 different affiliations in 24 countries across five continents.

Media impact of research

UK

Analysis shows that the report and symposium resulted in 156 media clips in the UK, with an estimated circulation of 173.5 million people. The diverse array of media included: national and regional publications in print and online, including *The Times, The Telegraph, Daily Mail, The Yorkshire Post* and *The Sunday Post*; TV coverage including BBC Breakfast, BBC News and Sky News; and radio interviews including on Radio 4's Today programme. The press coverage is estimated to have reached 70% of UK adults across all age groups, each seeing, reading or hearing something about the report in print, online or on TV on average 5.8 times.

International

An overview of the report was syndicated to news channels across the world (including media outlets in USA, India, Turkey, Malaysia and Taiwan). In addition, articles featuring a range of stories from the report appeared in individual news channels and publications in diverse countries including Australia (*The Australian*), China (ECNS – China News Service), the Philippines (*Inquirer online*), New Zealand (*The New Zealand Herald*) and the USA (CNN and Smithsonian online). Further, as the country focus for the report was China, the press release and part of the report were translated into Chinese.

Kew channels

The report, freely available online at stateoftheworldsfungi.org, reached a broad audience (with website usage tracked by Google Analytics). Social media was busy via our @KewScience twitter account and use of the #SOTWF hashtag.

Other impact beyond academia

Below are some examples of the report's impact since publication in September 2018. Further impacts are predicted as awareness of the importance of fungi continues to grow.

Government

An article on the report, published by the International Institute for Sustainable Development, was read by Alessandro Moscuzza (Climate Change and Environment Advisor, Department for International Development). This led him to contact Kew mycologists to discuss developing a portfolio of programmes for dealing with plastic ocean pollution.

Royal College of Art

First-year design students at the Royal College of Art became aware of research on plastic-degrading fungi through the report. They came to us for further discussions and incorporated this aspect of recycling into their final project report, poster and video.

Teaching and education

Teachers are using the report to convey the diversity and importance of fungi to audiences beyond academia, such as enthusiastic amateurs, conservationists, members of wildlife organisations and others.

Background to the research

State of the World's Fungi is the third report in the series State of the World's Plants and Fungi, initiated in 2015 as one of Kew's strategic outputs.

The report's ten chapters were led by our staff who worked with 112 collaborating co-authors from 18 countries. Here are examples of some of its contents:

Chapter 1

'Definition and diversity' was led by Kew mycologists Paul Cannon, Martyn Ainsworth, Ester Gaya, David Hawksworth and Paul Kirk, who have published more than 1,200 papers and are widely recognised as leaders of Ascomycota and Basidiomycota taxonomy and fungal nomenclature.

Chapter 2

'Fungal tree of life' was led by Ester Gaya who, together with her collaborators, has published extensively in this area, using the latest advances in molecular sequencing to shed light on the evolution of fungi.

Chapter 3

'New discoveries' was led by one of our leading taxonomists, Tuula Niskanen, who is a world authority on Cortinariaceae. She has more than 50 publications and typically describes 20–30 new species of fungi each year.

Chapter 5

'Positive plant–fungal interactions' was led by Laura Martinez Suz and included data arising from our ongoing research into ectomycorrhizal and endophytic fungi.

Chapter 10

'Conservation' was led by Martyn Ainsworth, a globally recognised expert in fungal conservation and the leading figure in red-listing fungi in Britain. Martyn is author of over 20 publications and reports on fungal conservation, including his recent report on assessing fungal conservation using an integrative approach.

Fungal collections and research at Kew

Kew hosts two web-based databases: Index Fungorum and Species Fungorum. Both are widely used with an average of one million hits per month, typically coming from 60–80 countries. We are one of the three repositories of new fungal species names in the world, a role we have performed since 2012 when it became compulsory to register new names.

Our mycological knowledge is backed up by the largest and most diverse fungarium in the world, comprising 1.25 million specimens and including 60% of the accepted genera and 35,000–50,000 type specimens from across the globe.

Our assets, including our scientists and collections, have made Kew a centre of mycological expertise at the heart of a large collaborative network – and provided the foundation for the compilation and delivery of *State of the World's Fungi*.

At-a-glance

- **Out on their own**
  Fungi are neither plants or animals – they are just themselves, and so have their own fungal kingdom. We may see 'mushrooms' when they are fruiting but for most of their life they are hidden away underground or inside plants or animals.

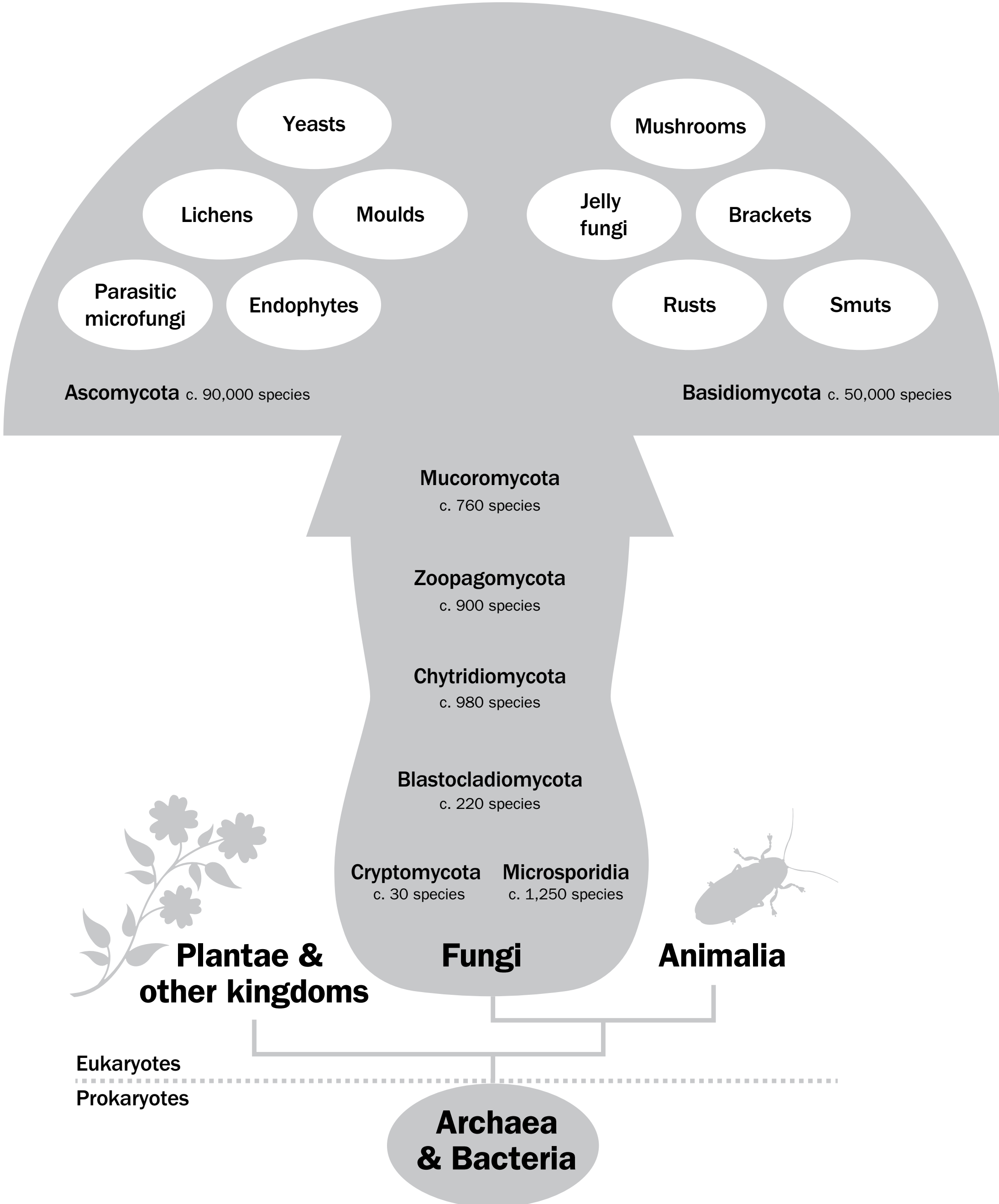
- **We need fungi**
  Humans have been using fungi in food, drinks and medicine for at least 6,000 years. In recent decades, science has revealed their role in important processes and in our everyday lives.

- **Benefits of fungi**
  Fungi recycle nutrients, capture carbon and prevent deserts forming in drought-prone regions. They also provide drugs such as statins and make biofuels, cheese and antibiotics – not to mention edible mushrooms.

- **Some wreak havoc**
  Fungi cause plant diseases such as rusts, wilts and mildews – a problem for gardeners, farmers and nature conservationists alike. They can also threaten global biosecurity.

- **Research on fungi at Kew**
  Kew has the largest Fungarium in the world with over 1.25 million specimens. We aim to understand how fungi evolved and how they are related to each other, not easy with new species being discovered at a phenomenal rate. In 2017, for example, 2,189 new species were described.

Our mycological knowledge is backed up by the largest and most diverse fungarium in the world, comprising 1.25 million specimens.



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