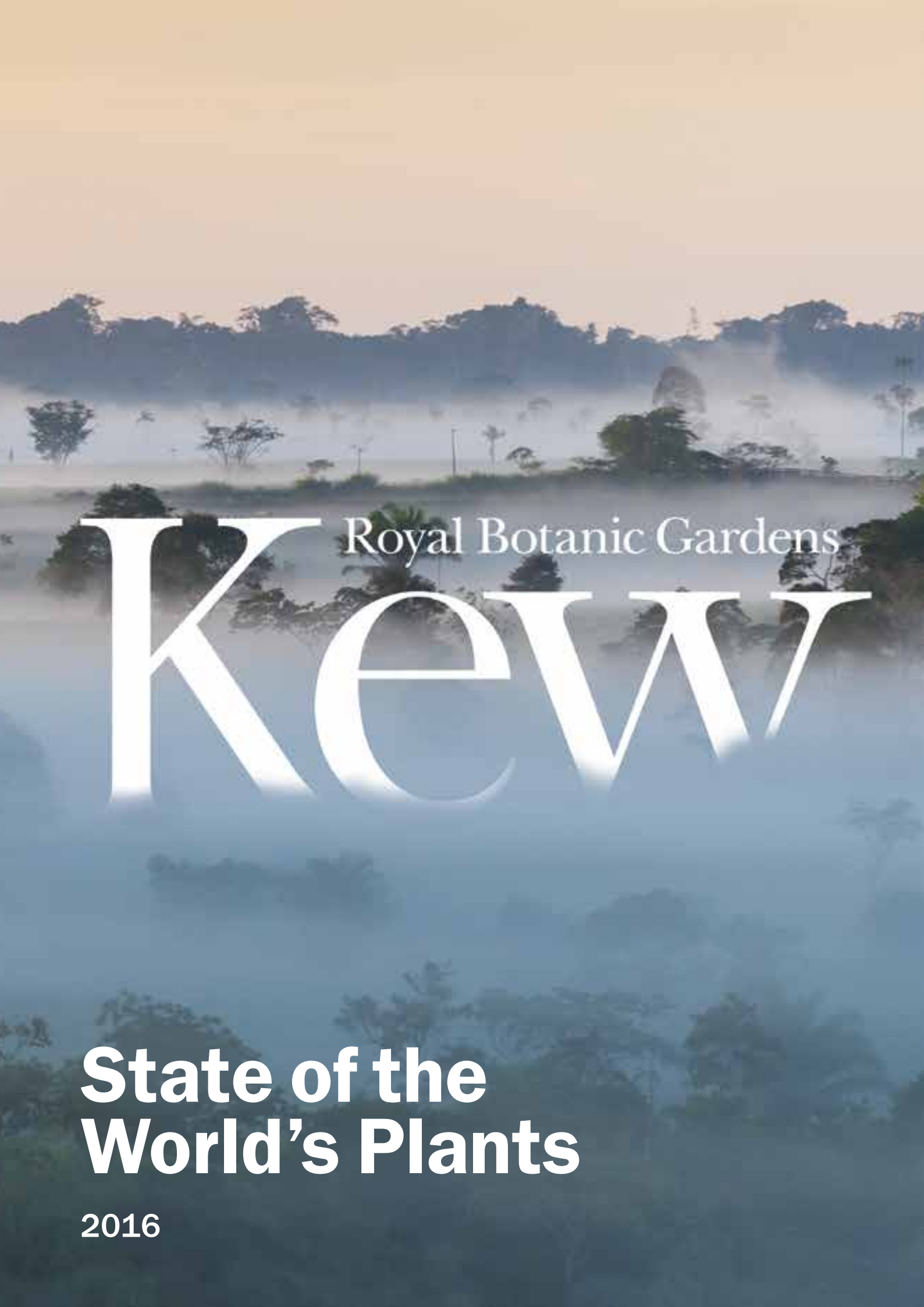


# State of the World's Plants

2016

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# Introduction to the State of the World's Plants

This is the first document to collate current knowledge on the state of the world's plants. A large team of researchers has reviewed published literature, scrutinised global databases and synthesised new datasets. The output presented here represents a status report on our knowledge of global vegetation as it stands in 2016, including a synthesis of existing information about vascular plants (Figure 1), new findings emerging from the review process, and an update on current knowledge gaps.

The report is in three sections. The first part describes what we currently know about plants: how many plant species there are, new plant discoveries in 2015, our current knowledge on plant evolutionary relationships and plant genomes, the number of useful plants, and the location of the world's most important plant areas. We also present a country-wide focus, this year on Brazil. The second part of the report assesses our knowledge of global threats to plants. In particular, we review the potential impacts of climate change, land-use change, invasive plants, plant diseases, and extinction risk. The third part details international trade, as well as policies and international agreements that are in place to deal with some of the threats.

There will inevitably be gaps in this report. We cannot claim to have covered all of the evidence currently available; this year is the beginning of an annual process, and in future years we will add to this knowledge base. However, by bringing the available information together into one document, we hope to raise the profile of plants among the global community and to highlight not only what we do know about threats, status and uses, but also what we don't. This will help us to decide where more research effort and policy focus is required to preserve and enhance the essential role of plants in underpinning all aspects of human wellbeing.

**Professor Kathy J. Willis**
Director of Science, RBG Kew

**Steve Bachman**
State of the World's Plants – Strategic Output Leader, RBG KEW

## MAIN QUESTIONS ADDRESSED IN THIS REPORT

**How many vascular plant species are known to science, and how do we know this?**

**How many vascular plant species new to science were named in 2015?**

**What is our current status of knowledge on the genetic diversity of plants and plant evolutionary relationships?**

**How many plant species currently have a documented use and what are they used for?**

**Which areas of the world are the most important to protect because of their incredible plant diversity?**

**What is the current status of plant knowledge in individual countries? A focus on Brazil.**

**How is climate change affecting plant species, populations and communities globally?**

**Where in the world are the greatest changes occurring in land-cover type and what are the main drivers of this change?**

**How many plant species are now classified as invasive and what are the predominant life-forms of these invasive plants?**

**What diseases pose the biggest threats to plants globally and where is the greatest concentration of research effort into these diseases?**

**What is our best estimation of how many plants are threatened with extinction?**

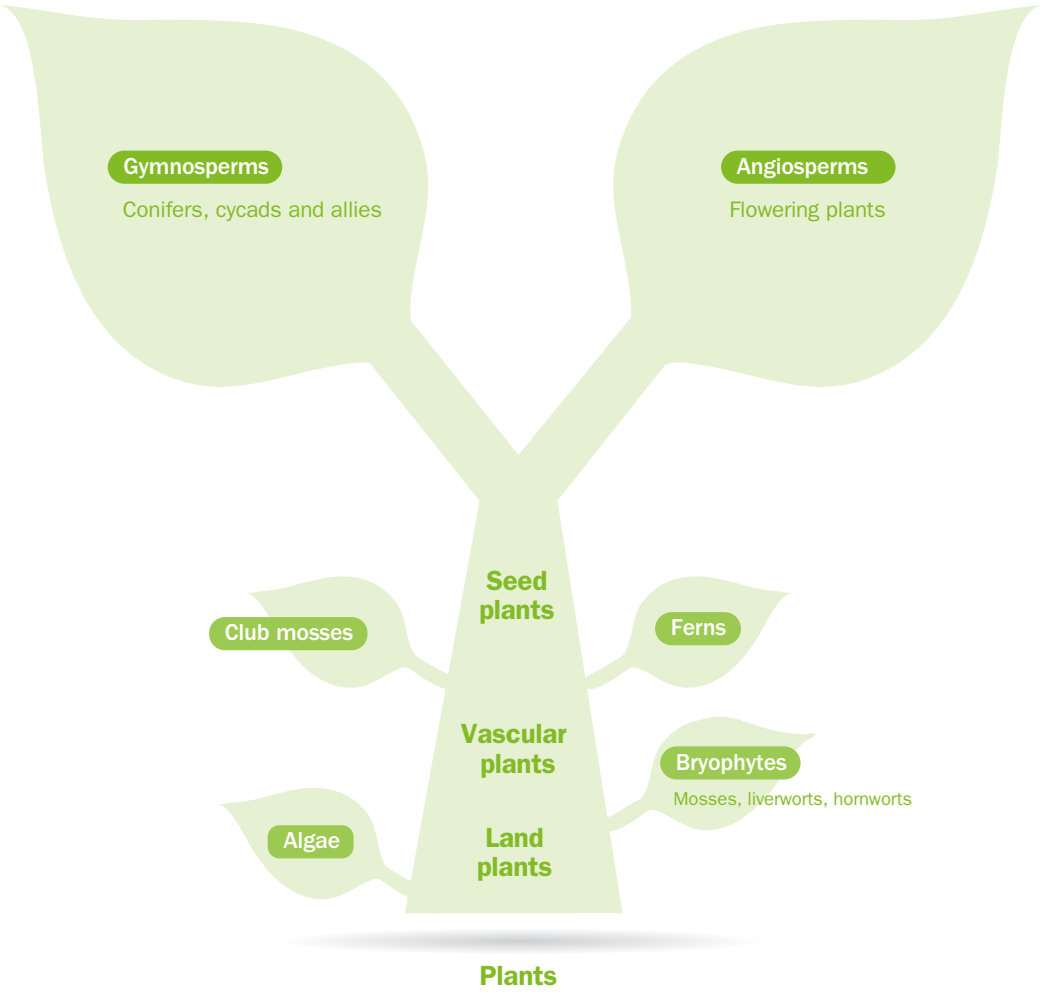
**What is the current status of international trade in endangered plant species and how effective are current policies at policing unsustainable or illegal international trade?**

**How many countries are now parties to the 2014 Nagoya Protocol on Access and Benefit Sharing of plant genetic resources and what are the early signs of its effectiveness?**

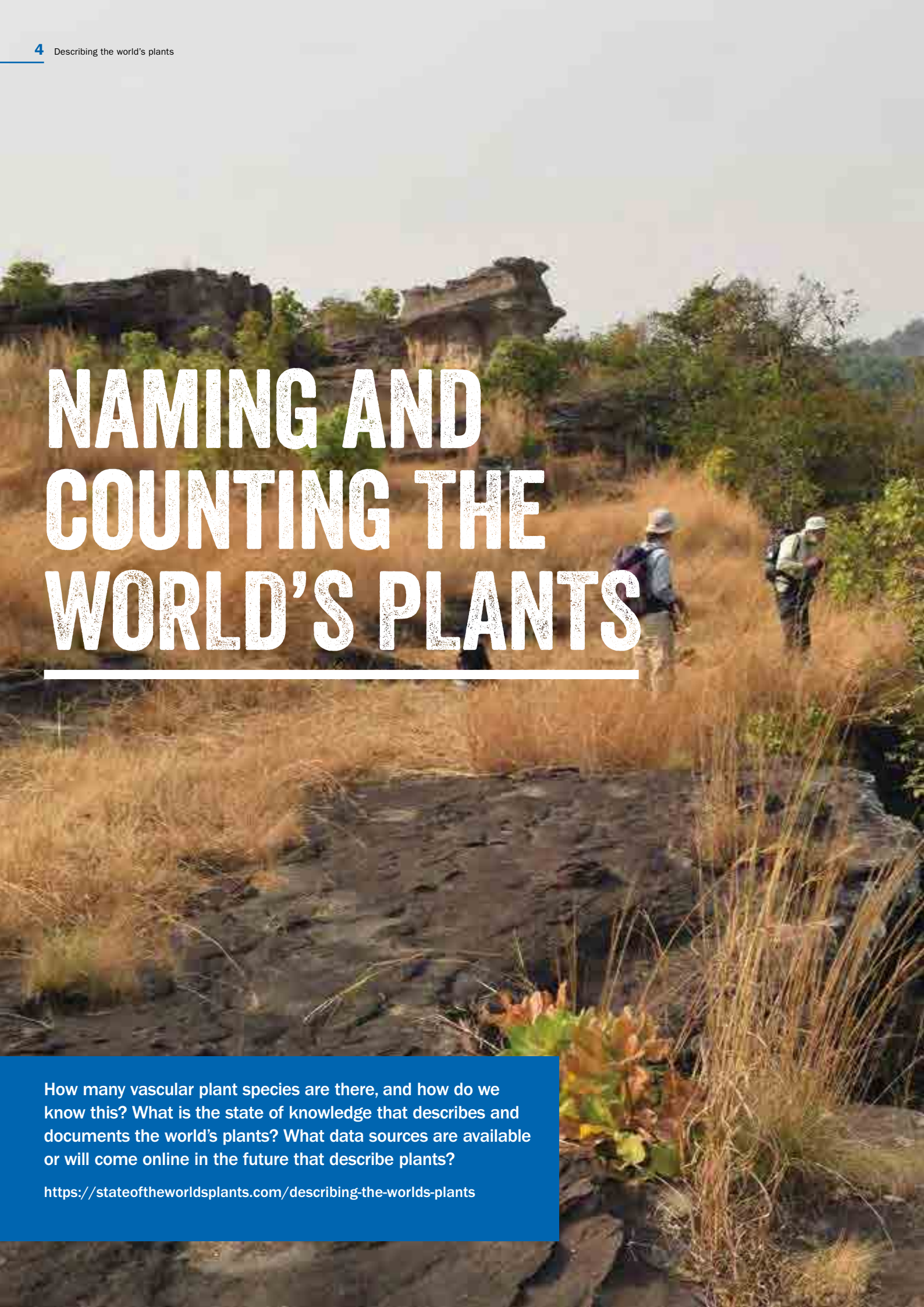
**FIGURE 1: SIMPLIFIED DIAGRAM TO ILLUSTRATE THE RELATIONSHIPS BETWEEN THE MAJOR GROUPS OF PLANTS**

Those groups at the bottom of the tree are the oldest in evolutionary terms; flowering plants (angiosperms) are the most recent group to evolve at around 140 million years ago.

This report focuses on all vascular plants. Vascular plants are characterised by a well-developed system of specialised cells that make up the vascular tissue. These cells provide the support that allows vascular plants to grow upright and a system for transporting water, minerals and products of photosynthesis around the plant.




**21%** OF GLOBAL PLANT SPECIES ARE CURRENTLY THREATENED WITH EXTINCTION ACCORDING TO IUCN RED LIST CRITERIA

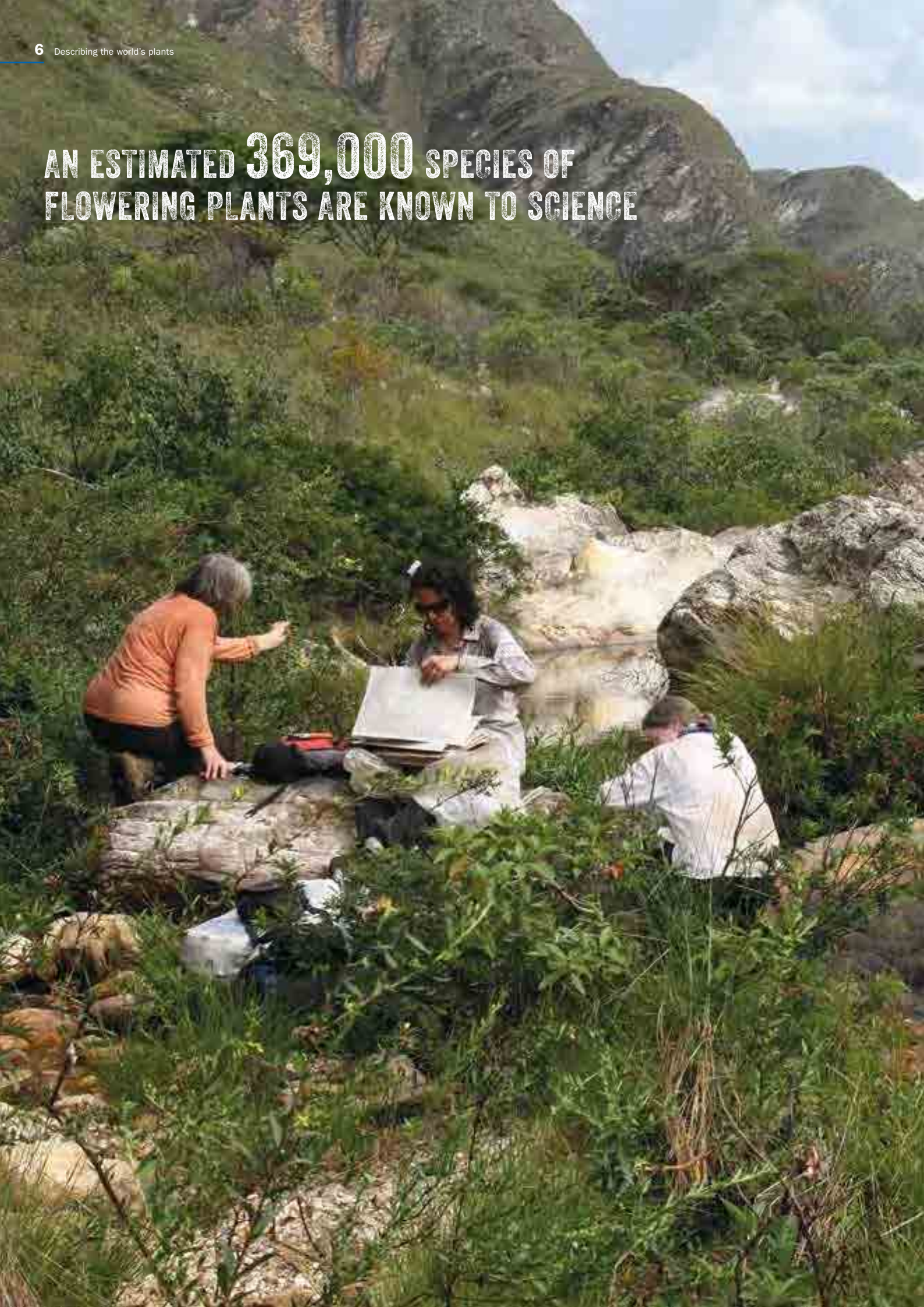


# NAMING AND COUNTING THE WORLD'S PLANTS

How many vascular plant species are there, and how do we know this? What is the state of knowledge that describes and documents the world's plants? What data sources are available or will come online in the future that describe plants?

https://stateoftheworldsplants.com/describing-the-worlds-plants

AN ESTIMATED
391,000
VASCULAR PLANT SPECIES
ARE KNOWN TO SCIENCE



# AN ESTIMATED 369,000 SPECIES OF FLOWERING PLANTS ARE KNOWN TO SCIENCE

# SCIENTIFIC NAMES PROVIDE THE BASIS FOR ACCURATE AND EFFECTIVE COMMUNICATION ABOUT PLANTS.

The correct application of scientific names is necessary for the synthesis and dissemination of information about the status of plant diversity. The classification of plants into groups that share a name and an associated set of characters also allows plants to be identified in an accurate and reproducible way, enabling both the safe use of plants in applied fields such as traditional medicine and the integration of digital datasets.

## HOW MANY VASCULAR PLANT SPECIES ARE THERE – AND HOW DO WE KNOW THIS?

There are three plant name resources at the heart of our current knowledge of plant diversity: The International Plant Names Index (IPNI, http://www.ipni.org), the World Checklist of Selected Plant families (WCSP, http://apps.kew.org/wcsp/) and The Plant List (TPL, http://www.theplantlist.org/).

The International Plant Names Index, covering vascular plants, is the product of a collaboration between Kew, Harvard University Herbaria and the Australian National Herbarium [1]. It provides the most comprehensive and regularly updated listing of scientific names for vascular plants. It currently contains 1,065,235 species names – with the large number of species names accounted for by the fact that many plants have more than one scientific name (averaging 2.7 names per vascular plant). This happens when the same plant species has been given different names, by different people at different times. The different names given to the same plant are called synonyms. Some synonyms reflect inadvertent (re)description of a species that had already been described by another researcher (taxonomic synonymy), but many other synonyms are the by-product of our improving understanding of the relationships among species, which results in species being 'moved' from one genus to another (nomenclatural synonymy). IPNI records only nomenclatural synonymy. Newly published names of families, genera, species and subspecies are added to the IPNI database daily, at an average rate of over 6,000 additions per year, of which most (70%) are for species. Of these, about 50% are species new to science and the remaining 50% are synonyms (Figure 2). Australia, Brazil and China are the top three source countries for the new species of vascular plants entered into IPNI over the past decade (Figures 3 and 4).

The World Checklist of Selected Plant Families is built on the foundation of plant names compiled in IPNI. The scope of WCSP is limited to seed plants, but importantly, it differs from IPNI in including information on global distribution and taxonomic synonymy. WCSP enables the user to check which names are considered to apply to the same species and which of these should be used, often termed the correct name or the accepted name.

Currently, the most comprehensive global list of all plant names is found in The Plant List, the product of an international collaboration but now managed by Kew. TPL is a working list of all known plant species, which aims to be comprehensive for all species of vascular plant (flowering plants, conifers, ferns and their allies) and of bryophytes (mosses, liverworts and hornworts). It provides the accepted scientific name with links to synonyms for three quarters of these species. It also provides a consensus overview of taxonomic synonymy but differs from the WCSP in being neither peer-reviewed nor updated; it was last revised in 2013. TPL appeals to a large number of users because

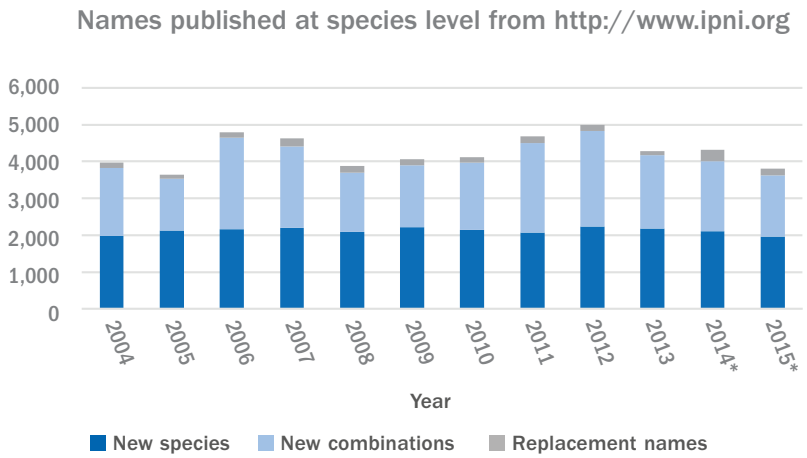
### FIGURE 2: PROGRESS TOWARDS COMPLETING THE GLOBAL INVENTORY OF PLANT DIVERSITY

Numbers of vascular plant species described as new to science have regularly exceeded 2,000 per year for the past decade. The bar chart shows species of vascular plants new to science published each year (deep blue), as well as names at species level resulting from nomenclatural changes arising as a result of improved understanding of the relationships among species (new combinations and replacement names, pale blue and grey, respectively) [2].

**New combination** – a new name based on a legitimate, previously published name, which is a basionym [2]

**Replacement name** – a new name based on a (legitimate or illegitimate) previously published name, which now becomes a synonym [2]

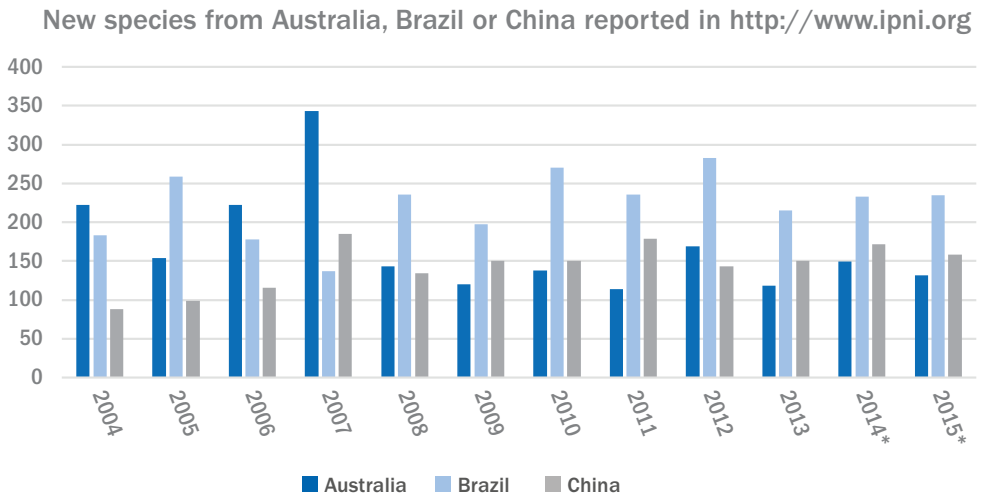
**New species name** – the name of a new taxon validly published in its own right [2]




*These are underestimates, as not all names published in 2014–15 have yet been indexed in IPNI

## FIGURE 3: WHICH COUNTRIES ARE THE SOURCE OF MOST NEW VASCULAR PLANT SPECIES NAMES?

The top three source countries for the identification of new species of vascular plants are Australia, Brazil and China, as has been the case since the 1990s.




*These are underestimates, as not all names published in 2014–15 have yet been indexed in IPNI

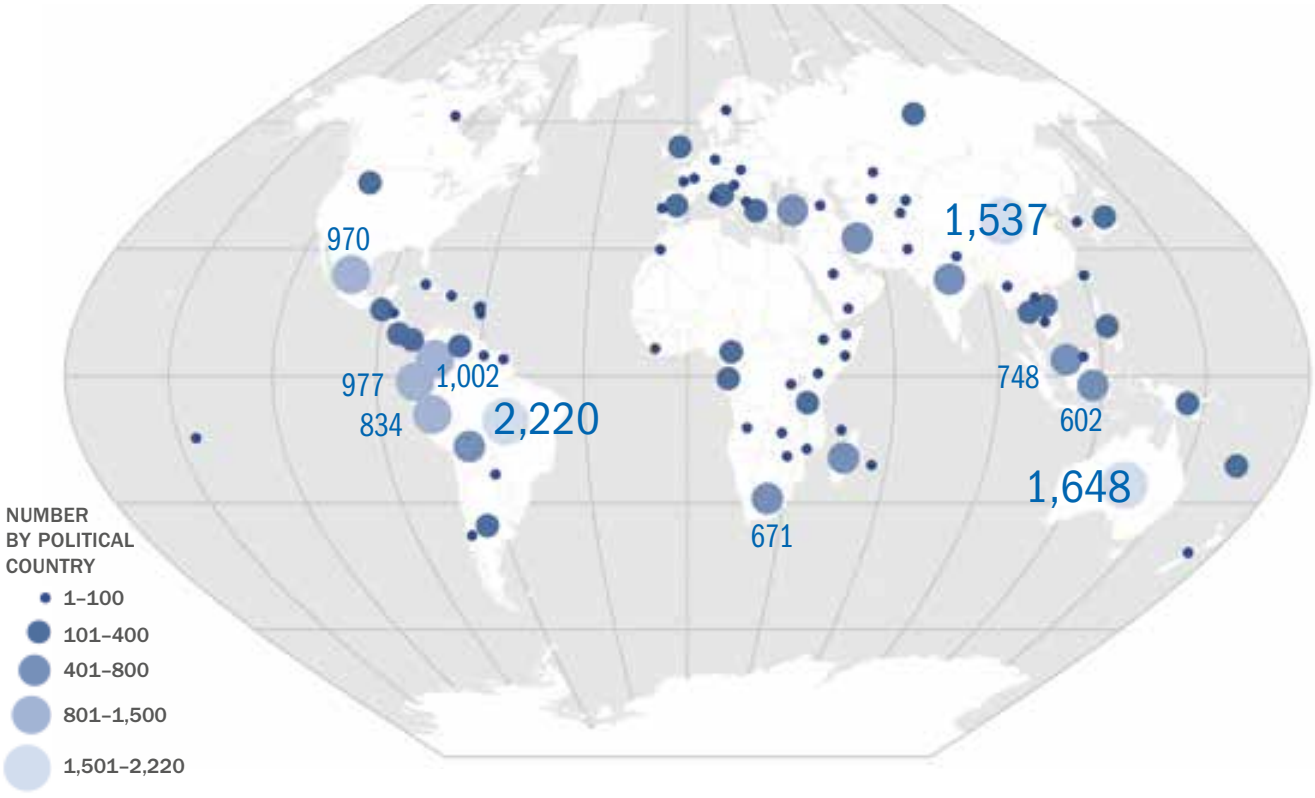
**THE TOP 3 SOURCE COUNTRIES FOR SPECIES NEW TO SCIENCE ARE BRAZIL, AUSTRALIA AND CHINA**

of its comprehensive coverage, the fact it presents users with a single accepted name and its user-friendly interface.

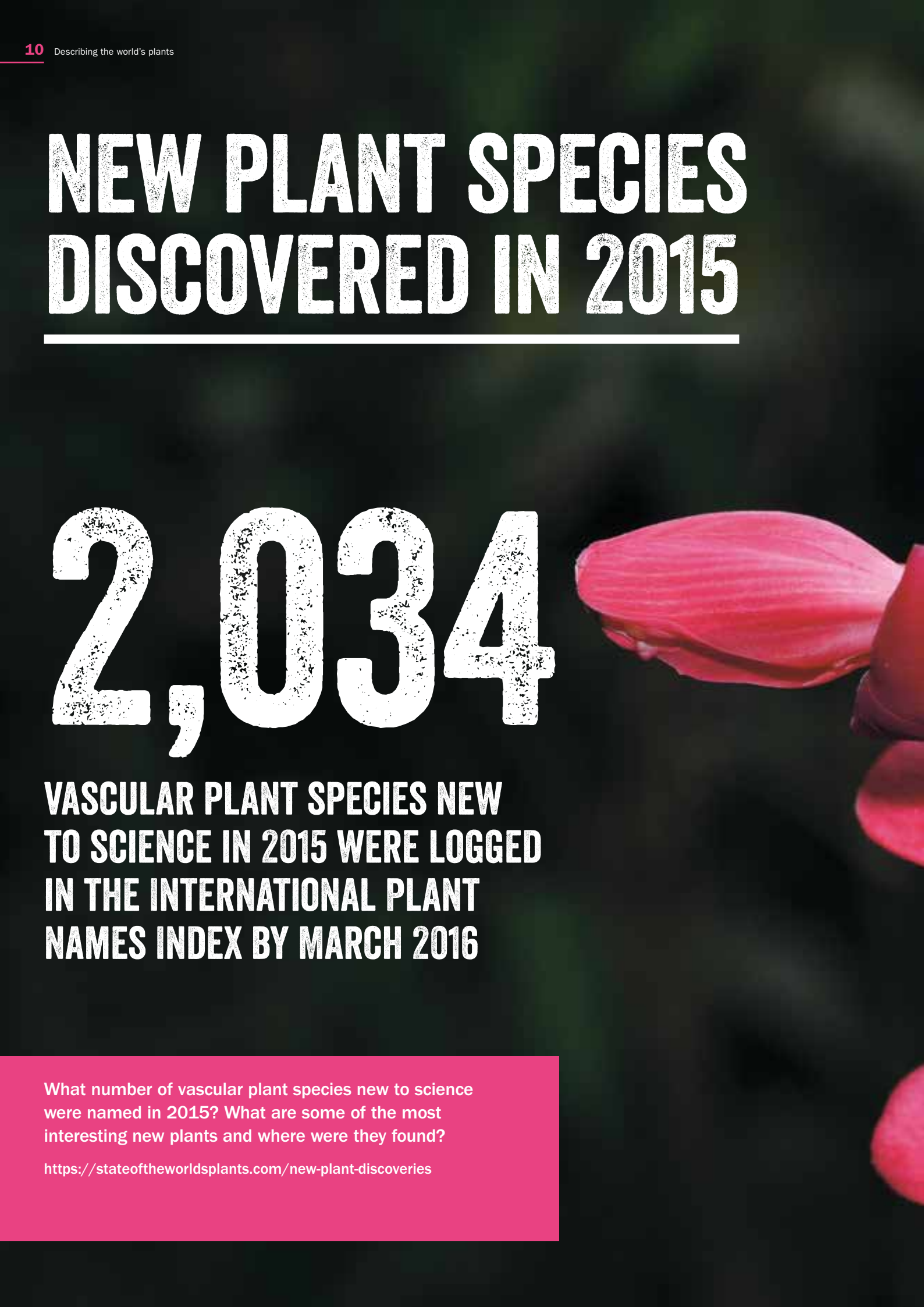
In summary, IPNI provides details of the names of vascular plants; WCSP provides the correct or accepted name and global distribution for one third of these plants (33%), with about another third (31%) in an advanced stage of preparation; while TPL provides a list of all known plants, addressing gaps in WCSP's coverage of seed plants and also including some information on the accepted names of bryophytes, though not all names in TPL are linked to an accepted name. These three plant name resources also contribute to numerous other products and services such as e-monocot (http://e-monocot.org/), the Catalogue of Life (http://www.catalogueoflife.org), Flora do Brasil 2020 (http://reflora.jbrj.gov.br/reflora/listaBrasil/) and Kew's Medicinal Plant Name Services (http://mpns.kew.org/mpns-portal/), as well as to the work of plant scientists worldwide. However, many users face the problem of deciding which plant names resource is most appropriate for their needs. This is because, despite the coverage of these three resources, there are still significant gaps in knowledge and no one resource which unambiguously links every scientific plant name to a recognized species. This can lead to much debate about the 'true' number of plant species currently known to science [3–5].

Currently in development and due for launch in late 2016 is the Plants of the World Online Portal (POWOP), which will collate all of the above plant species information. POWOP is being developed by Kew with input from many partner organisations. By doing this, we hope to solve the issues of multiple databases providing different information on plant names; POWOP will provide a single entry point to enable the dissemination of plant information at levels accessible to all. In the meantime, we have used a modified version of the methodology devised by Paton et al. [6] to determine the most up-to-date number of known plant species for this report. This is based on the observation that there is a strong linear relationship in WCSP between the number of species recognised in a particular plant family and the number of plant names which have been used for these species. Assuming that the linear relationship observed in the names of these well-researched families also applies to the seed plant families not yet completed in the WCSP, and also to families of ferns and fern allies, the number of vascular plant species known to science can be estimated from the total number of species names for vascular plants currently found in IPNI. Using this approach, our current best estimate for the number of vascular plant species known to science is approximately 390,900, of which approximately 369,400 are angiosperms.

**FIGURE 4: SOURCES OF NEW VASCULAR PLANT SPECIES NAMES ENTERED INTO IPNI BETWEEN 2006 AND 2015**



# NEW PLANT SPECIES DISCOVERED IN 2015



## 2,034

**VASCULAR PLANT SPECIES NEW TO SCIENCE IN 2015 WERE LOGGED IN THE INTERNATIONAL PLANT NAMES INDEX BY MARCH 2016**

What number of vascular plant species new to science were named in 2015? What are some of the most interesting new plants and where were they found?

https://stateoftheworldsplants.com/new-plant-discoveries

*Dendrobium cynthiae*

*Oberholzeria etendekaensis*

>>

At
**1.5 METRES TALL,**
this species is one of the largest sundews known to science.

*Drosera magnifica*

*Gilbertiodendron maximum*

*Ochna dolicharthros*

<<

The largest and heaviest of all new species described in 2015, weighing in at an estimated
**105 TONNES**

*Gilbertiodendron ebo*

*Canavalia reflexiflora*

## THE MOST EXCITING OF THE NEW PLANT SPECIES DISCOVERED IN 2015 WERE FOUND AS A RESULT OF RECENT FIELDWORK, PARTICULARLY IN SOME OF THE LEAST-STUDIED REGIONS IN THE WORLD.

New species of trees, shrubs and herbaceous plants have been discovered, including some new plants from well-known horticultural families, food crops, grasses and carnivorous plants. In addition to those found during fieldwork, there are also new species that have been discovered as a result of re-examining herbarium sheets, which often contain plant specimens collected many years ago. A full list of the new species can be found at the IPNI website (http://www.ipni.org). Some of the more unusual finds are described below.

The largest and heaviest of all new species described in 2015, weighing in at an estimated 105 tonnes, was *Gilbertiodendron maximum,* one of eight threatened, leguminous, canopy *Gilbertiodendron* trees found in the Cameroon-Congolian African rainforest [7]. Growing to 45 m tall, with a massive trunk up to 1.4 m in diameter, this critically endangered giant is endemic to (i.e. unique to a defined location in) Gabon.

Among the other legume species new to science is a tree of *Amburana* from north-east Brazil, which has shiny red seeds and sap that is used locally as a soap. Perhaps the most exciting legume discovery of 2015 is *Oberholzeria etendekaensis*, a succulent shrublet, which is not only a new species but also in a new genus. It is known only from a single locality with 30 individuals in the Kaokoveld Centre of Plant Endemism, north-western Namibia.

*Canavalia reflexiflora*, a striking papilionoid legume related to the Brazilian jack bean (a crop wild relative), was also described in 2015. Rather than being discovered in the field, this plant was first recognised by a Brazilian researcher who was examining specimens in the Kew herbarium. Subsequent fieldwork revealed that this rare species no longer survives at the location where it was originally collected. It persists, however, in another area of Minas Gerais, Brazil, at a site subject to environmental protection but nonetheless threatened by coffee cultivation. Its red flowers with a reflexed standard (petal) of similar length to the wing and keel petals suggested that the species is hummingbird-pollinated, unlike the other species of *Canavalia*, which are bee-pollinated. Field observations have recently corroborated this.

From the rainforests of South East Asia, six new species of liana, shrub and tree from the primrose family (Primulaceae), placed within the genera *Embelia, Maesa* and *Systellantha*, have been identified and published. Five new custard-apple and ylang-ylang relatives in the genera *Alphonsea, Artabotrys, Meiogyne* and *Monoon,* mainly from Malaysia and Indonesia, have also been described. Also from South East Asia, more than 90 new species of *Begonia*, a genus well-known to horticulturalists, have been published in 2015. Of these, 15 species are from Sumatra, many from a single collection or location.

The discovery of a new grass, *Sartidia isaloensis,* in Madagascar reveals a fascinating story. The extensive grasslands of the central highlands have long been thought to be populated by invasive African species, which replaced forest destroyed by humans; but new research shows that the flora is, in fact, largely made up of native, fire-adapted species of *Aristida.* The related, relictual, non-fire-adapted *Sartidia isaloensis* survives only on the ledges of sandstone cliffs in the Isalo National Park, out of reach of annual fires. The only other *Sartidia* species known to have existed in Madagascar is believed to be extinct.

Carnivorous plants new to science in 2015 include *Nepenthes barcelonae*, a climbing pitcher plant, which was found in remnant cloud forest on a peak in the Sierra Madre range of Luzon, Philippines. In Brazil, a new insect-eating plant, *Drosera magnifica*, was discovered. This species grows to an incredible size of 1.5 m, making it one of the three largest sundews known to science [8]. Known only from a single small population at the top of a mountain in Minas Gerais, this species was first discovered on Facebook, when a sundew specialist was reviewing photos taken years earlier by an orchid hunter.

Also published in 2015 were 13 new taxa from the genus *Allium*, a genus which includes cultivated onion, garlic, scallion, shallot, leek and chives [9]. These new species include five new onions, all related to the well-known cultivated onion *Allium saxatile.*

New discoveries in the morning glory and bindweed family (Convolvulaceae) include five species of *Convolvulus* from Eurasia and 18 species of *Ipomoea* from Bolivia, among which, excitingly, is a close relative of the sweet potato, *Ipomoea batatas.*

Among the new orchids discovered and published in 2015 is *Dendrobium cynthiae*, named for its grower in the USA, who acquired it from a dealer. The pretty white flowers have a green lip. The wild origin of the species is unknown, but is conjectured to be New Guinea. The largest orchid species published in 2015, at 3 m tall, with three or four reed-like stems, is a slipper orchid, *Selenipedium dodsonii*, uncovered during research for a book on the slipper orchids of South America.

Several of the new species published in 2015 are already presumed extinct. One is a 12–15 m tall tree species of Ghana and Ivory Coast, where its dry forest habitat has been reported as cleared for agriculture or destroyed by fires. *Tarenna agnata*, of the coffee family (Rubiaceae), has not been seen alive for 50 years; this species was discovered from herbarium records. Another species that is thought to be extinct is the smallest known flowering plant species published in 2015, a minute, 3–4 mm tall herb of the waterfall-specific family Podostemaceae. The only known locality for this species, *Ledermaniella lunda*, is now the site of a hydroelectric dam, and diamond-mining has turned the river waters brown and turbid, a death-sentence for plants of this family.

# PLANT EVOLUTIONARY RELATIONSHIPS AND PLANT GENOMES

**How complete is our understanding of plant evolutionary history and relationships? How does increased understanding inform policy and management?**

https://stateoftheworldsplants.com/plant-genomics

THERE ARE NOW
139
VASCULAR PLANT SPECIES WITH ASSEMBLED WHOLE-GENOME SEQUENCES ONLINE

## THE SPECTACULAR DIVERSITY OF PLANT LIFE ON EARTH TODAY IS CONNECTED BY ITS SHARED EVOLUTIONARY HISTORY, WITH THE EVOLUTIONARY LINKS BETWEEN SPECIES RECONSTRUCTED AS A VAST, BRANCHING, PLANT TREE OF LIFE.

The Plant Tree of Life (phylogenetic tree) is a graphical depiction of how taxa are related to each other (see Rosindell & Harmon [10] for an example). Formerly such trees were built using the physical features of specimens, particularly their flower characteristics, but in recent decades the process has been revolutionised by the addition of DNA sequence data – most recently for over 280,000 plant taxa [11]. The new approach has significantly enhanced our understanding of flowering plant evolution and led to the development of an increasingly robust classification system by the Angiosperm Phylogeny Group (an international collaboration in which Kew is a leading player). The most recent update recognises 416 families grouped into 64 orders [12].

We now know that an understanding of evolutionary relationships in the Plant Tree of Life can greatly accelerate the discovery of new taxa, particularly in less well-known groups, and can act as a sign-post for discovering additional species of relevance to human wellbeing, impacting medicines, foods, biofuels and fibres.

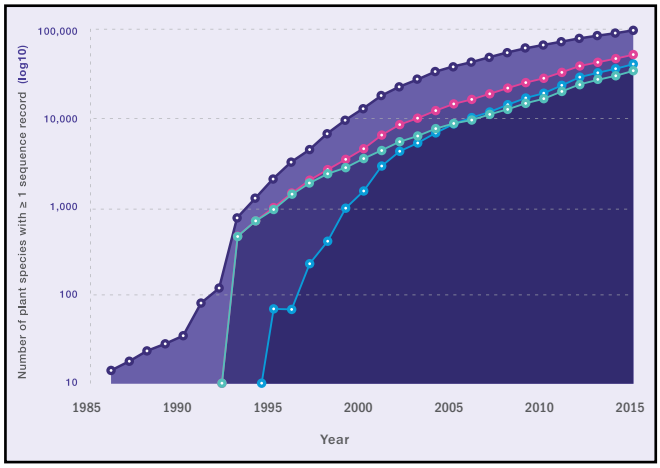
Knowledge of the Plant Tree of Life is also key to unlocking the potential of Earth's natural capital and in mitigating against biological risks to our food security and biodiversity [13–16]. For example, knowing the relationships amongst crop species gives plant breeders a head-start in developing new crops that can address challenges posed, for example, by climate change, pathogens, soil degradation and rising fertiliser costs while maintaining or enhancing productivity [17].

Until recently, the use of DNA in the construction of the Plant Tree of Life relied on sequence data from short 'molecular barcode' sections of the genome (see Figure 5). These short stretches of DNA often represented data from just one or a few genes and comprised just a few kilobases of DNA. However, a typical plant genome contains between 20,000 and 50,000 genes, and the total amount of DNA (=genome size) can range from 63 to 150,000 megabases [18]. Clearly, to understand evolutionary relationships amongst species more fully and to gain deeper insights into how plant genomes function, more complete genomic datasets (comprising both DNA and RNA data) are needed. This is now possible given the recent advances in high-throughput sequencing technologies, which are capable of generating gigabases of sequence data in a single experiment. When combined with genome size information (http://data.kew.org/cvalues/), which makes it possible to estimate both costs and genome coverage, these data can be used to reconstruct whole genomes and transcriptomes, enabling comparative genome mapping and the construction of ever more complex multi-sequence trees [19].

Such advances in sequencing are opening up unprecedented opportunities in many fields of biology. This is perhaps most notable in the field of plant breeding, given that the majority of vascular plant species with whole-genome sequences to date are crops [17, 20]. Nevertheless, the increasing realisation of the genetic potential held within crop wild relatives (which, broadly speaking, are the cousins of crops and ancestral species from which current crops have evolved) for enhancing the productivity, nutritional content and resilience of crops to environmental change means that they too are increasingly becoming a focus of whole-genome sequencing and transcriptome projects [20].

Currently, there are 139 vascular plant species with assembled draft whole-genome sequences online (http://www.ncbi.nlm.nih.gov/assembly/). As sequencing technologies continue to advance and costs plummet still further, this number is predicted to increase rapidly. Such developments will enable many more areas of the Plant Tree of Life to be explored, providing data that are crucial for meeting the growing needs of an expanding human population (e.g. for fighting crop diseases, or for guiding the search for new therapies and industrial products) and for characterising rare and endangered species to underpin conservation of the world's biodiversity.

### FIGURE 5: NUMBER OF VASCULAR PLANT SPECIES WITH AT LEAST ONE REGION OF DNA SEQUENCED SINCE 1986 AND REPORTED IN GenBank




Figures refer to the number of species in GenBank with:
– 'Any sequence' (any sequence data at all)
– '*rbcL* gene' (only sequences marked as copies of the *rbcL* gene)
– '*matK* gene' (only sequences marked as copies of the *matK* gene)
– '*matK* or *rbcL*' (only *matK* or *rbcL* gene copies)

SOURCE: http://www.ncbi.nlm.nih.gov/genbank/

## FEWER THAN 0.1% OF VASCULAR PLANT SPECIES HAVE COMPLETED WHOLE-GENOME SEQUENCES

## CURRENT STATUS OF PLANT GENOMICS IN NUMBERS

A review of data available on the National Center for Biotechnology Information (NCBI) Taxonomy Browser (http://www.ncbi.nlm.nih.gov/taxonomy) as of 31 December 2015, with synonyms reconciled against The Plant List (version 1.1; http://www.theplantlist.org/) shows that:

APPROXIMATELY

**106,700**

SPECIES OF VASCULAR PLANTS ARE REPRESENTED BY AT LEAST ONE DNA REGION IN GENBANK.

OF THESE SPECIES

**57,286**

VASCULAR PLANT SPECIES HAVE BEEN SEQUENCED FOR ONE OF THE MOST COMMONLY USED MARKERS IN PLANT PHYLOGENETICS (I.E. *RBCL* AND /OR *MATK*).

# USEFUL PLANTS

AT LEAST

# 31,128

PLANT SPECIES CURRENTLY HAVE A DOCUMENTED USE

How many plant species currently have a documented use and what are they used for? Where in the world are the most important areas for the collection of wild plants for current and future human use?

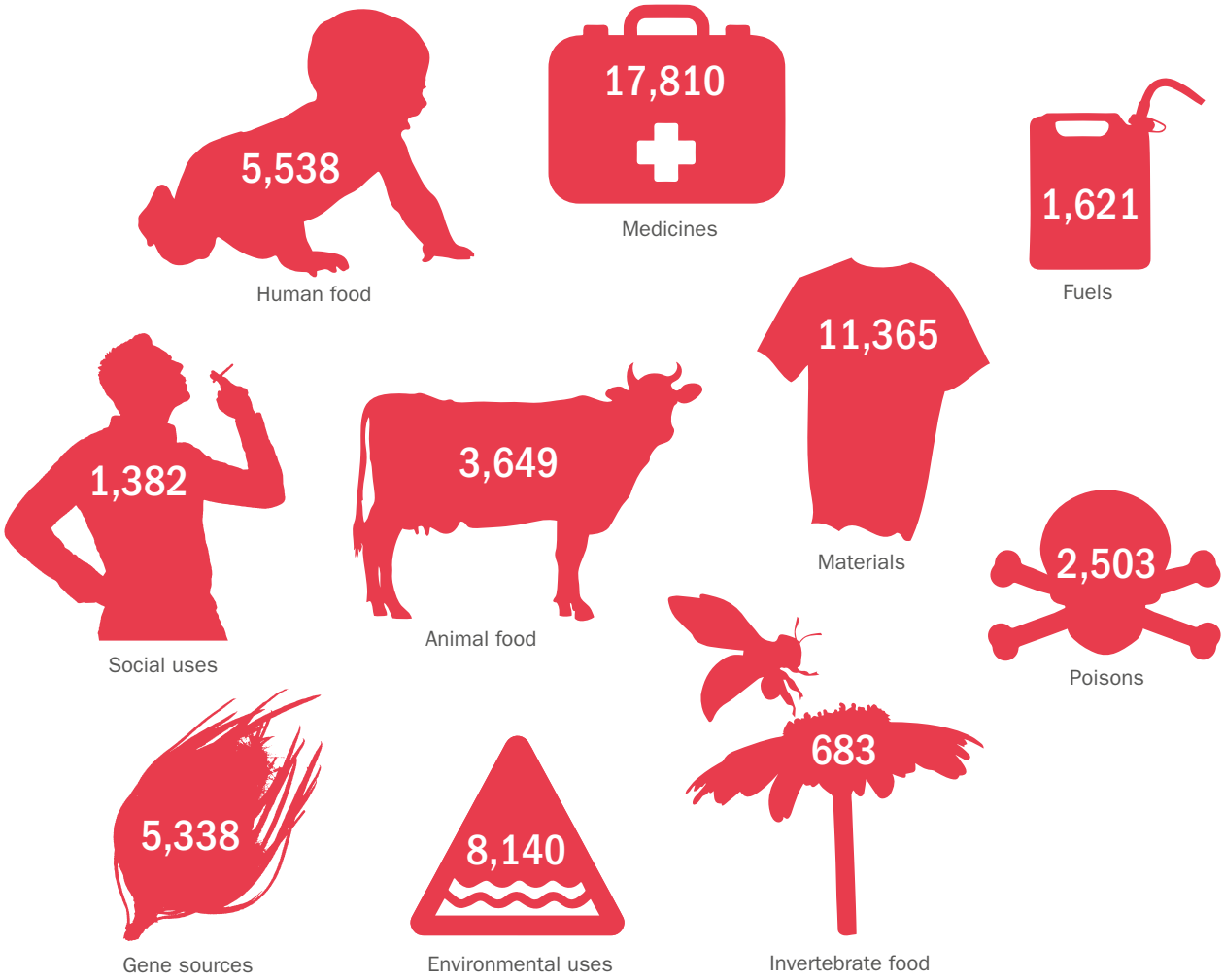
https://stateoftheworldsplants.com/useful-plants

## THE TERM 'USEFUL PLANTS' IS USED TO DESCRIBE PLANT SPECIES WHICH HAVE BEEN DOCUMENTED AS FULFILLING A PARTICULAR NEED FOR HUMANS, ANIMALS OR THE WIDER ENVIRONMENT.

There are a number of databases that catalogue useful plant species, including Plant Resources of Tropical Africa (better known as PROTA, http://www.prota4u.info/), the Medicinal Plant Names Service (MPNS, http://mpns.kew.org/mpns-portal/) and the Germplasm Resources Information Network (GRIN, http://www.ars-grin.gov/). For this report, we compared plant species across 11 databases and can reveal that over 30,000 plant species have at least one documented use (see Figure 6), with some having multiple uses. Perhaps unsurprisingly, the largest number of plants with a documented use are those that have been utilised as medicines. The next most common usage group are those plants used in materials – this includes plants used for textiles and building materials. Plant species recorded as useful environmentally include those used to restrict erosion, as firebreaks or in agroforestry. There are currently 8,000 different plant species in this category. Around 5,000 plant species provide human food; a further 5,000 are possible gene sources – species that are potentially useful in the genetic improvement of crops. The next most common category of useful plants comprises non-human foods; these include invertebrate food plants, such as those eaten by insects (e.g. silkworms) that are used by people, plants that encourage pollinators (e.g. bee plants), and those eaten by animals. Plant species recorded as being used as poisons, fuel or for social uses (including plants used as intoxicants or for religious reasons) number the fewest, but there are still more than 1,300 plant species in each of these categories.

Aside from the plants that are currently in use, where should we be focusing our collection efforts to include future useful plants? One set of plant species widely recognised as being of critical importance to global food security are crop wild relatives, which broadly speaking are the cousins and

**FIGURE 6: NUMBER OF PLANT SPECIES IN EACH USE CATEGORY**



ancestral species from which our crops evolved. Many of the plant species that are currently cultivated have gone through a massive genetic bottleneck over the thousands of years of domestication, resulting in the selection of traits that provide higher yields and desired qualities [21]. Unfortunately, this has resulted in severely depleted gene pools [22]. Moreover, it has also been found that the traits that result in higher yields are often not the same as those that enable resilience to changing climates or to pests and diseases, leaving higher-yielding crops particularly vulnerable to these threats [23].

Crop wild relatives have long been recognised as providing an essential pool of genetic variation that can help to drive the improvement of our crops into the future. Back in the 1920s, the Russian geneticist Nikolai Vavilov was among the first to inspire the international community to conserve crop wild relatives to equip breeders with the resources needed to address new challenges [24, 25]. Now, with the global challenges we are facing relating to population size, land-use change, plant diseases and pests, there is an increasing urgency to find and conserve crop wild relatives so that they can be used in crop breeding programmes [21]. Having access to this large and diverse pool of genetic resource is essential if we are to furnish crops with the valuable traits that their wild relatives possess, enabling resilience to climate change, pests and diseases, and ultimately underpinning global food security [26–28].

A recent inventory has revealed that there are currently 3,546 prioritised global plant taxa identified as crop wild relatives [29]. Kew's Millennium Seed Bank (MSB) includes 688 crop wild relatives among its over 78,000 accessions, but preliminary assessments of the geographic and ecological diversity of collections of crop wild relatives worldwide have revealed substantial gaps [29, 30]. Given that many of the wild populations of these species are under considerable threat due to land-use and climate change [31, 32], there is an urgent need to conserve those species not adequately represented in current germplasm collections (for example, as seeds or tissues in gene banks [33]).

In a recent study, researchers conducted a detailed analysis of the extent of representation in genebanks of the wild relatives of 81 key food crops from 24 plant families [34]. This involved modelling the geographic distributions of 1,076 wild relatives of these crops. Potential geographic and ecological diversity in these distributions was then compared to that which is currently accessible in genebanks, and the results revealed worrying gaps. Over 70% of taxa were identified as high priorities for further collecting in order to improve their representation in genebanks, and over 95% were found to be insufficiently represented in regard to the full range of geographic and ecological variation of their native distributions. In particular, there are considerable gaps in the conservation coverage of banana, aubergine and sorghum crop wild relatives. By comparison, the diversity of wheat, sunflower and tomato is relatively well-represented in genebank collections.

As well as identifying the crop wild relatives that require urgent collecting and subsequent conservation in genebanks, the analysis was also used to identify geographical areas that present a high concentration of multiple crop wild relatives (richness spots), and collecting hotspots where multiple crop wild relative taxa yet to be collected are likely to be found (Figure 7). The richness spots largely align with traditionally recognised centres of crop diversity [24], although the analysis also identified a number of less well-recognised areas, such as central and western Europe, the eastern USA, south-eastern Africa, and northern Australia, which also contain considerable richness. The most critical collecting gaps are found in the Mediterranean and Near East, in western and southern Europe, in South East and East Asia, and in South America. The analysis shows significant gaps in collections within a great majority of the crop genepools analysed.

The Adapting Agriculture to Climate Change Project [33] has started to fill the collection gaps identified by this research. With the support of this project, national partners across Europe, Asia, America and Africa are collecting crop wild relatives for *ex situ* conservation and genetic resources for crop breeding (http://cwrdiversity.org/project/map/).

# CROPS AND THEIR WILD RELATIVES

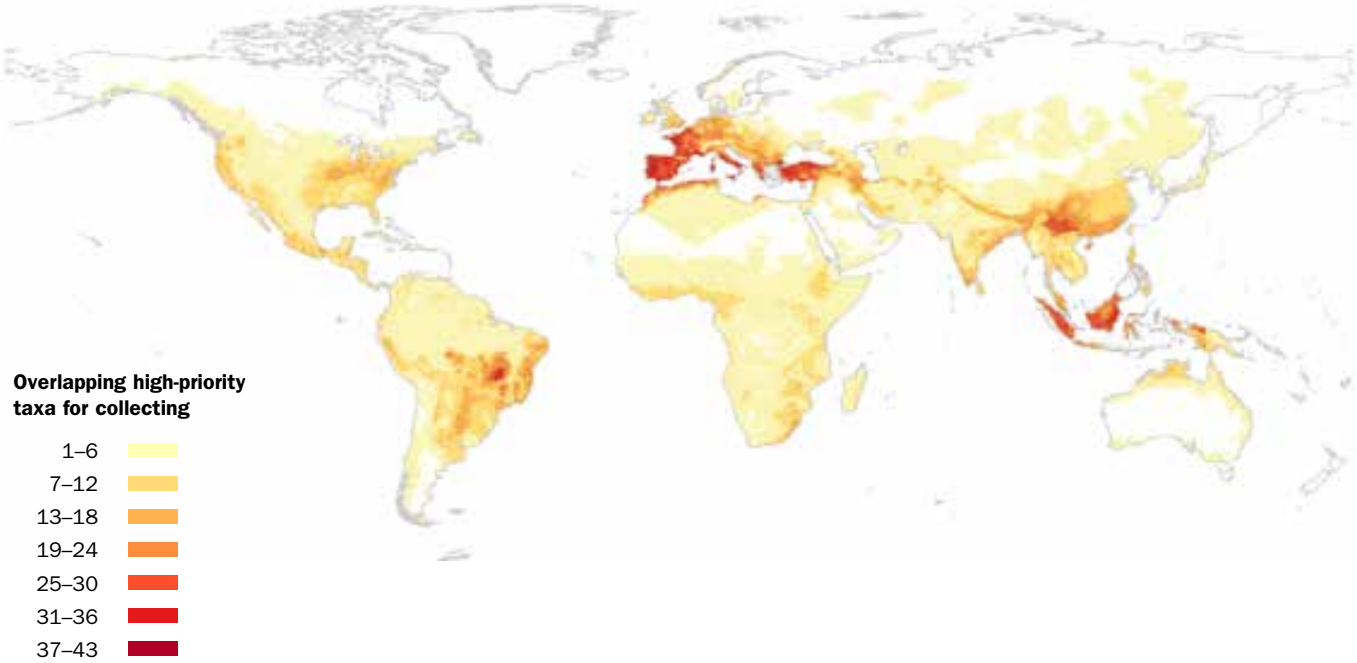
**BANANA** ↑ **CROP:** Cultivated *Musa*
↓ **CWR:** *Musa acuminata*

**GUINEA YAM** ↑ **CROP:** *Dioscorea rotundata cayenensis*
↓ **CWR:** *Dioscorea abyssinica*

**FINGER MILLET** ↑ **CROP:** *Eleusine coracana*
↓ **CWR:** *Eleusine indica*

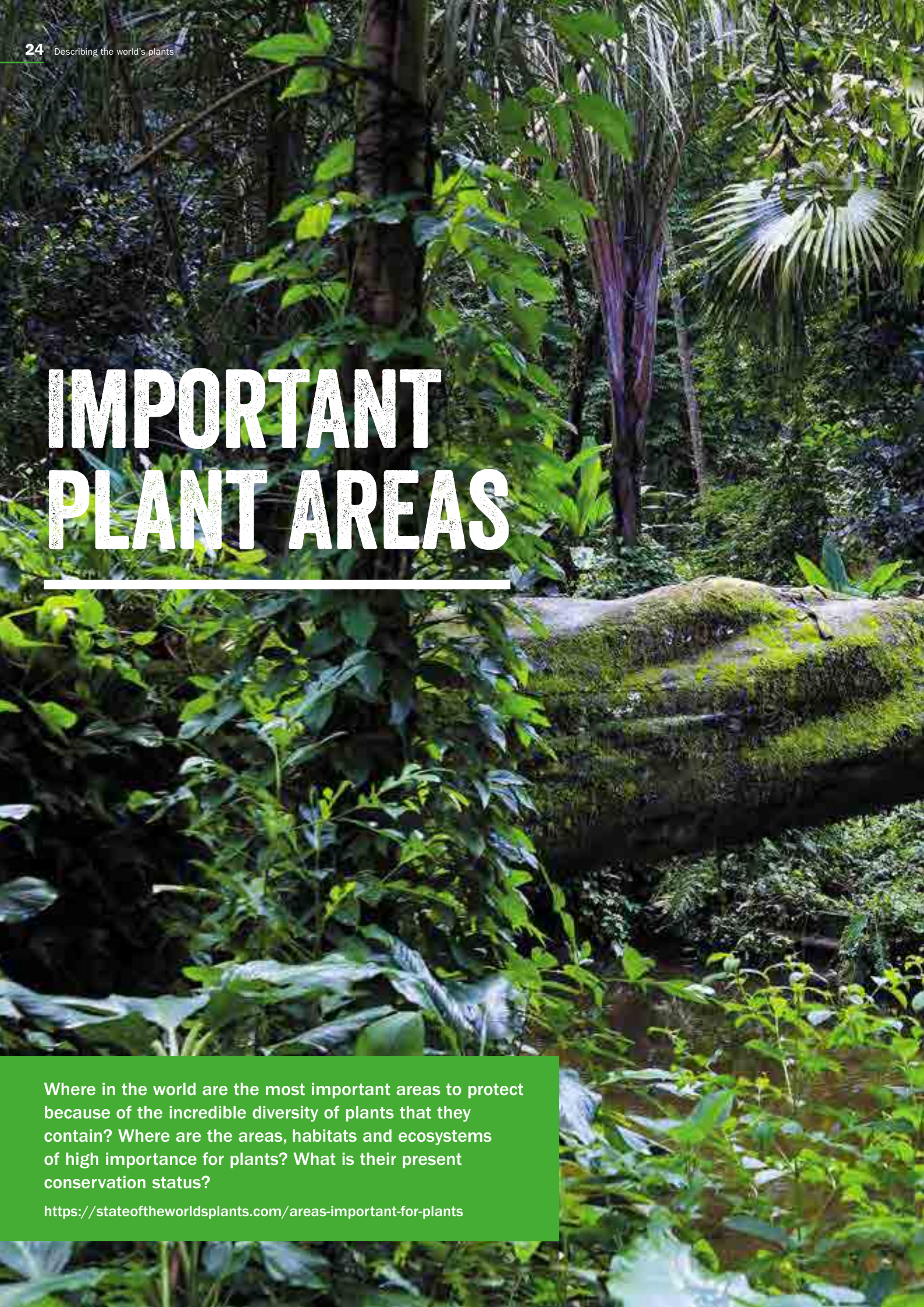
## FIGURE 7: GEOGRAPHIC AREAS (RICHNESS SPOTS) AND COLLECTING HOTSPOTS FOR CROP WILD RELATIVE TAXA

The map displays geographic regions where high-priority crop wild relative taxa are expected to occur and have not yet been collected and conserved in genebanks. Darker red colours indicate greater overlap of the potential distributions of under-represented taxa, i.e., where greater numbers of under-represented crop wild relative taxa occur in the same geographic area.




SOURCE: CASTAÑEDA-ÁLVAREZ & KHOURY (2016) [34]

CONSIDERABLE GAPS IN GENEBANK COLLECTIONS OF THE CROP WILD RELATIVES OF BANANA, AUBERGINE AND SORGHUM MAKE THESE CROPS PARTICULARLY VULNERABLE TO CLIMATE CHANGE, AND TO PEST AND PATHOGEN OUTBREAKS



# IMPORTANT PLANT AREAS

Where in the world are the most important areas to protect because of the incredible diversity of plants that they contain? Where are the areas, habitats and ecosystems of high importance for plants? What is their present conservation status?

https://stateoftheworldsplants.com/areas-important-for-plants

# 1,771

## IMPORTANT PLANT AREAS HAVE BEEN IDENTIFIED GLOBALLY BUT VERY FEW CURRENTLY HAVE CONSERVATION PROTECTION

## SOME AREAS OF THE PLANET EXHIBIT AN INCREDIBLE QUANTITY AND DIVERSITY OF PLANTS, WITH MANY UNIQUE SPECIES. BUT MANY OF THESE AREAS ARE DEGRADING OR DISAPPEARING ENTIRELY UNDER THE ASSAULT OF INCREASING THREATS, INCLUDING LAND-USE CHANGE, CLIMATE CHANGE, PESTS AND DISEASES.

With resources to safeguard plant diversity so scarce, the race is on to identify sites that are in most urgent need of conservation.

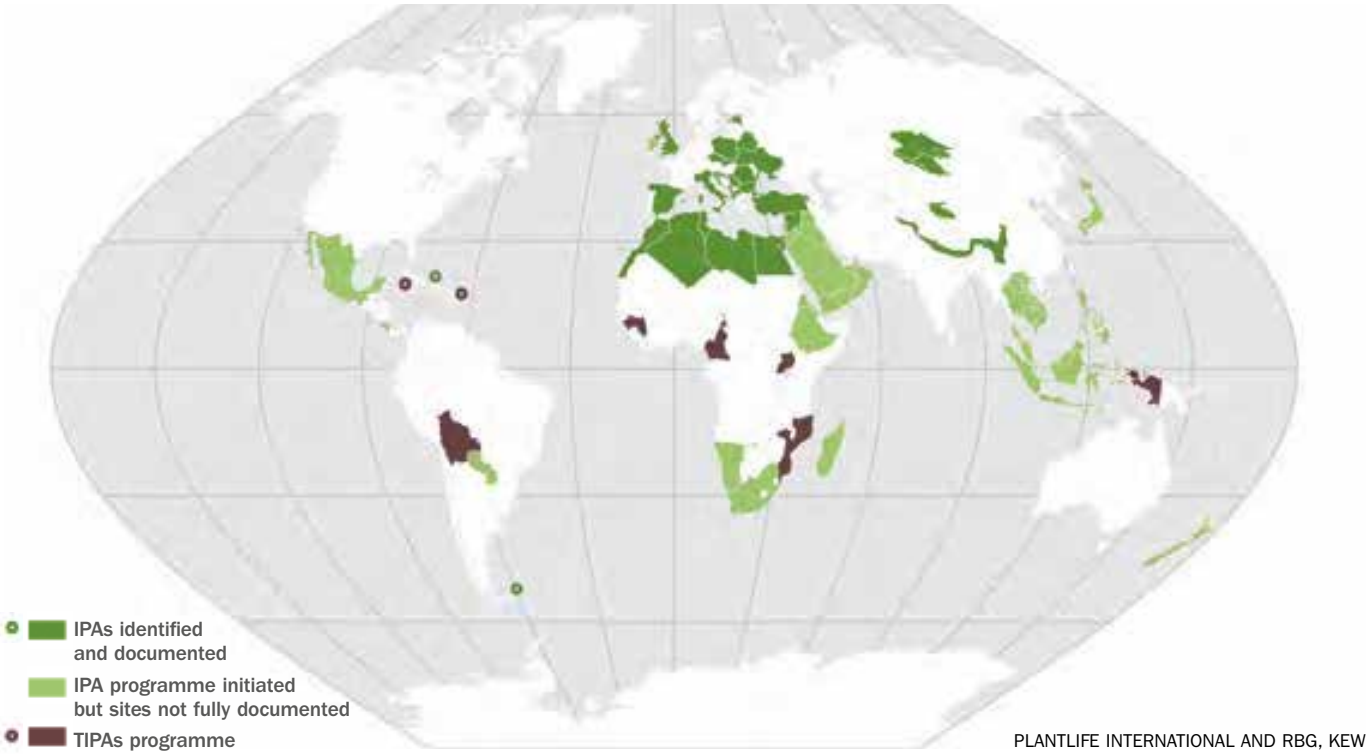
Important Plant Areas (IPAs) is a scheme that determines priority sites by using three key measures of importance: threatened species; exceptional botanical richness; and threatened habitats [35]. The IPA process enables national and regional experts to identify their key sites in order to promote effective conservation planning and site safeguarding, using practical but scientifically rigorous criteria. Within the revised criteria being launched in 2016, IPA identification also takes into account socio-economically and culturally important plants, both as a measure of botanical richness and as a way of engaging the communities who live and work within IPAs in their long-term conservation and sustainable management. IPAs are formally recognised as a conservation tool under Target 5 of the Convention on Biological Diversity (CBD) Global Strategy for Plant Conservation [36].

Plantlife International (PI) were instrumental in establishing the IPA criteria in the early 2000s. PI has helped to designate over 1,750 IPAs in 16 countries across Europe, North Africa and the Middle East [37–39] (see Box 1: IPAs in the UK). PI are currently working with national partners in Europe, especially in the Balkans, to engage communities and decision-makers in valuing and conserving their IPAs. Significant progress has also been made globally, with 69 countries having undertaken at least an initial assessment of their IPAs [38], but a clear gap remains in tropical regions (see Figure 8). In response to this, Kew has launched the first ever IPA campaign focusing entirely on the tropics. The Tropical Important Plant Areas (TIPA) programme (RBG Kew 2016; http://science.kew.org/strategic-output/tropical-important-plant-areas) is committed to identifying IPAs in seven tropical countries or regions in its first phase: Bolivia, Cameroon, Guinea, Indonesian New Guinea, Mozambique, Uganda and the Caribbean UK Overseas Territories (see Box 1: TIPAs in Guinea).

Beyond site recognition, the most pressing need is to move towards protection and/or sustainable management of IPAs. One in four European IPAs currently has no legal protection, many have no active management plan and a significant number are imminently threatened [38]. Monitoring and management of IPA sites outside of protected areas will ultimately rely on local networks, and it is therefore imperative that local communities and authorities are invested in IPA programmes from the outset (see Box 1: IPAs in Turkey).

National IPA initiatives will also play an important role in contributing plant data to the International Union for Conservation of Nature (IUCN)'s Key Biodiversity Areas (KBAs) initiative, which aims to identify sites that contribute significantly to the global persistence of biodiversity.

**FIGURE 8: COUNTRIES THAT HAVE DESIGNATED IMPORTANT PLANT AREAS (IPAS) OR ACTIVE IPA PROGRAMMES**




PLANTLIFE INTERNATIONAL AND RBG, KEW

## BOX 1: EXAMPLES OF IMPORTANT PLANT AREAS

### TROPICAL IPAS (TIPAS) IN GUINEA

Guinea has the highest plant species diversity in West Africa (Schnell, cited in [40]), with many rare and unique species and genera that are increasingly threatened by habitat loss and degradation. In 2015, Kew and the UGAN-Herbier National de Guinée initiated the first IPA programme in tropical West Africa, twinned with a Plant Red Listing project [41]. Strong links have been developed with the government's Ministry of Environment, Water and Forests, who are keen to use data on Guinea's threatened species and habitats to inform strategies to expand protected areas. Through partnering with Guinée Ecologie, a non-governmental organization (NGO) which specialises in community outreach, the project will also promote community-led management of IPAs that fall outside formal protection areas. Through this work, the partners hope to secure the future for such remarkable and rare species as *Pitcairnia feliciana*, the only bromeliad (pineapple family) native outside the Americas, which is restricted to a small corner of Guinea, and the mass-flowering forest herbs *Brachystephanus oreacanthus* and *Isoglossa dispersa*, both assessed as globally vulnerable in 2014 [42].

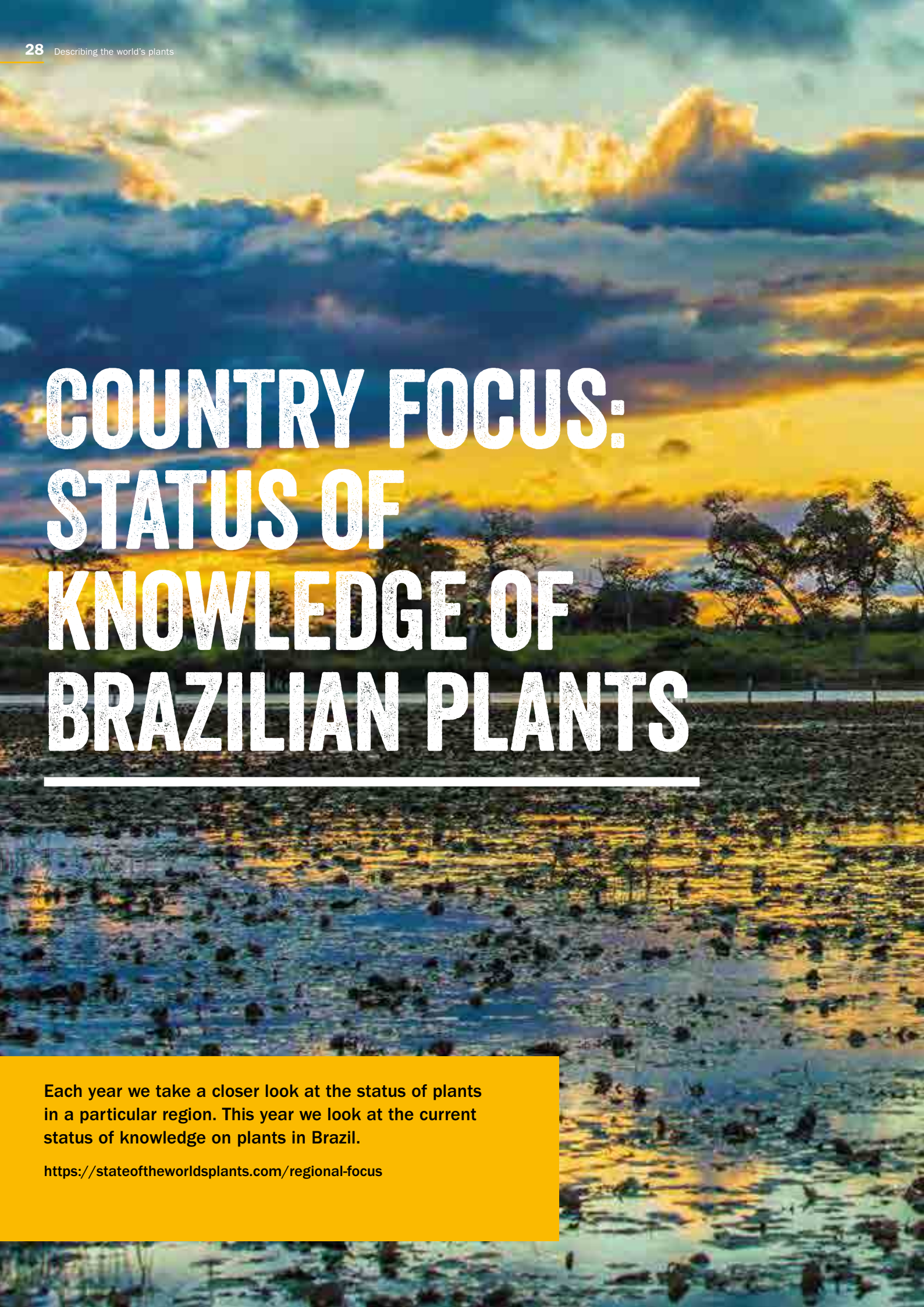
### IPAS IN THE UK

The UK has very few endemic species, but it does have globally important habitats such as the Atlantic woodlands and Celtic Rainforests. As a result of this, 165 IPAs have been identified in the UK from Caithness to Cornwall [43]. They include the Lizard in Cornwall, the Brecklands of East Anglia, The Great Orme in North Wales, the wetlands of Caithness and the largest UK IPA – the West Coast IPA in Scotland.

IPA identification is also being undertaken in several United Kingdom Overseas Territories (UKOTs). In the Falkland Islands, for example, the 17 IPAs identified in 2007 by Falklands Conservation [44] are being incorporated into the Falkland Islands Government's Biodiversity Strategy. In the Caribbean, Kew and the National Parks Trust of the Virgin Islands have just secured funding to run a programme of IPA identification on the British Virgin Islands.

### IPAS IN TURKEY

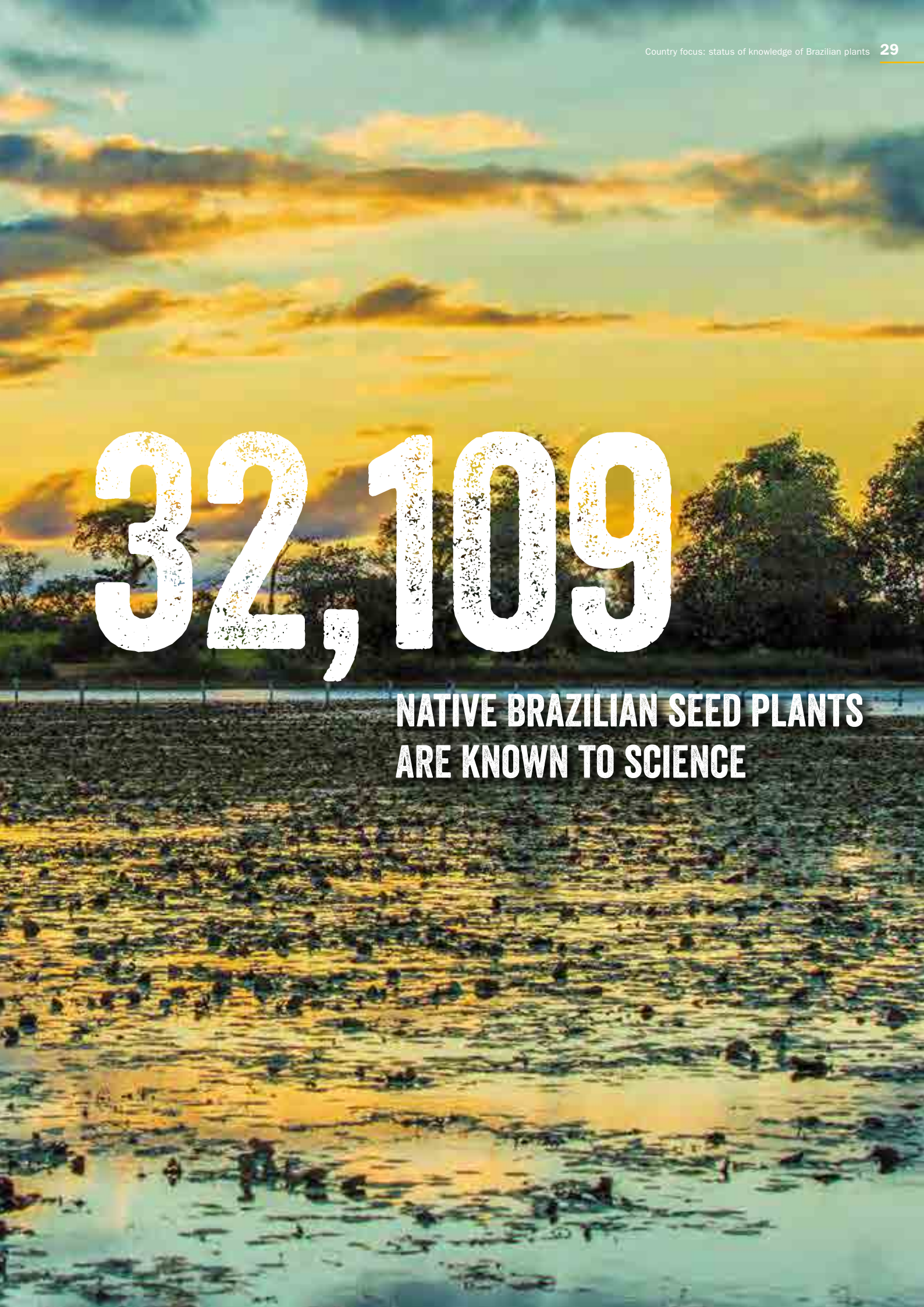
Turkey was the first country in the world to identify its IPAs through the collaboration of 40 scientists from 20 universities and the support of WWF Turkey, Flora and Fauna International, and the University of Istanbul [45]. Turkey has one of the richest floras in the temperate world with at least 8,897 native vascular plant species, including 3,022 endemics. These globally important species and habitats continue to face the familiar threats of habitat fragmentation, landscape change and lack of awareness of their importance. By the early 2000s, the Turkish team had identified 122 IPAs and had assessed the threats to each site as moderate, urgent or critical. More recently, the Rubicon Foundation in the Netherlands has helped to set up a network of IPA volunteers who undertake site and species monitoring and raise awareness of the importance of these sites [46].



# COUNTRY FOCUS: STATUS OF KNOWLEDGE OF BRAZILIAN PLANTS

Each year we take a closer look at the status of plants in a particular region. This year we look at the current status of knowledge on plants in Brazil.

https://stateoftheworldsplants.com/regional-focus



# 32,109

## NATIVE BRAZILIAN SEED PLANTS ARE KNOWN TO SCIENCE

## BRAZIL IS HOME TO MORE SEED PLANTS THAN ANY OTHER COUNTRY IN THE WORLD AND IS ALSO A RECORD-BREAKER IN TERMS OF THE RATE AT WHICH KNOWLEDGE OF ITS FLORA IS GROWING.[47]

In 2010, Brazil published a list of all known Brazilian plant and fungal species [47], meeting Target 1 of the Global Strategy for Plant Conservation [36] adopted by the parties to the Convention on Biological Diversity. Since then, Brazil's efforts to document its native plant diversity have gone from strength to strength. Several recent achievements are notable:

- 1,471 seed plant species have been added to the national list since 2010, bringing the total to 32,109 native species, of which 18,423 are known only from Brazil [48]
- more than 5,000 names have been added to the national list, including many synonyms, which enhance the list's usefulness as a central point of reference for all Brazil's plant information and possible duplication of plant names [48]
- basic distribution data at the level of biome, state and habitat are now available for all known species
- conservation status according to IUCN Red List criteria has been re-evaluated for all Brazilian plant species considered to be threatened [48], and there have been regional assessments of rare Cerrado plants [49] and of all species endemic to the state of Rio de Janeiro (http://cncflora.jbrj.gov.br/portal/).

Three notable groups of plants in Brazil are the bromeliads, the cacti and the Cerrado daisies.

### BROMELIACEAE

Almost totally exclusively Neotropical in its distribution, this is the family of the pineapple and of ornamental airplants (*Tillandsia* species): rootless epiphytes which obtain moisture and nutrients from rain and mist.

Brazil's Atlantic Rainforest harbours 911 of the 1,343 Brazilian Bromeliaceae species. The majority of these (804) are known only from the Atlantic Rainforest and most species (783) are unknown outside Brazil [48]. Bromeliaceae occur as terrestrial or rock-dwelling species, and can survive in multiple environments. The Bromeliaceae is the second largest family of epiphytes in the Atlantic Rainforest, contributing over a quarter (26.2%) of the biome's epiphytic species. Adaptations of these epiphytes to their aerial environment include their peltate scales (which absorb water in the absence of roots) and their water-tanks formed by the tightly packed leaf-bases. Peltate scales are found in approximately 750 (or 56%) of the Brazilian species.

Over 88% of the Brazilian species of Bromeliaceae that are currently recognised as threatened occur in the Atlantic Rainforest biome. The Bromeliaceae feature prominently in the Brazilian Red List [48]. Of the 371 species evaluated, 202 are categorised as threatened (15% of Brazil's 1,343 species). Many more are still awaiting assessment (972, around 72%). Amongst the most frequent threats are destruction and degradation of habitats due to agriculture and urbanisation, which impact upon endemic species with restricted ranges.

### CACTACEAE

Apart from a single species, the cactus family is purely American in its distribution. There are currently 1,480 known species of cacti. One of the three areas of major diversity for these plants is eastern Brazil, and two of the six regions with the largest numbers of threatened cacti are in Brazil [50]. A highly restricted area in southern Rio Grande do Sul in Brazil and Uruguay (area = c. 500 km$^2$) represents the global peak both in absolute numbers of threatened cacti (33) and in the proportion of its cacti that are threatened (89%). Eastern Brazil (Bahia/Minas Gerais) is also home to many threatened cacti, although the proportion that is threatened is lower (45%).

In total, the IUCN Red List reports 134 threatened species of Brazilian cacti (47.3% of the 283 species known from Brazil). Over 28% of these threatened species of Cactaceae occur in the Caatinga biome.

Threats to cacti include habitat degradation due to livestock and increasing mechanized soybean cultivation, quarrying and mining. Indiscriminate plant collection also causes degradation, impacting the already restricted, dwindling populations.

### COMPOSITAE: CERRADO DAISIES

Daisies and their relatives in the Compositae family make up one of the three largest plant families in the world; they are most species-rich in the tropics.

There are 2,049 known species of daisy in Brazil, with 1,213 (almost 60%) occurring in the Cerrado biome. Almost half (566) of these are not found anywhere else in the world [48]. One of the key adaptations of daisies in the fire-prone Cerrado open vegetation is a thick rootstock, known as a xylopodium.

Less than 20% of the native species of this family (242) have been evaluated through Brazil's Red List [49] but it is estimated that 63% of them are threatened. The restricted distribution of daisies makes them vulnerable to habitat degradation, to the frequent fires started by cattle farmers in order to improve pastures, and to increasing mechanized soybean cultivation.

## BOX 2: SIX VEGETATION BIOMES ARE RECOGNISED IN BRAZIL [51, 52]

### AMAZÔNIA (AMAZON RAINFOREST) →

Found in northern and central-western Brazil, and comprising a great variety of vegetation forms, of which the flooded and tall *terra firme* lowland forest predominate [53].

**COVERAGE:** 49.3% of the Brazilian territory, extending well beyond Brazil's borders into Bolivia, Peru, Ecuador, Colombia, Venezuela, and the Guianas [54].

**THREATS:** The so-called arc of deforestation spans the south-eastern Amazon Basin. Many hydroelectric projects affect major rivers, and more localized damage is caused by mining at different locations within the Basin [55]. As vast tracts of this biome are still underexplored [55, 56], it is possible that a reasonable proportion of its biodiversity remains unrecorded while large spans of this biome undergo severe modification.

### ← CERRADO (CENTRAL BRAZILIAN SAVANNA)

Predominantly grassland with woody elements and encompassing a diverse mosaic of upland vegetation types known as *campos rupestres* [57].

**COVERAGE:** 23.9% of the Brazilian territory, with marginal continuous extensions in north-eastern Paraguay and Bolivia [58, 59].

**THREATS:** Large-scale agricultural change was late to reach this biome which has relatively poor soils. Advances in agricultural mechanisation now make it possible to convert large tracts to the cultivation of soybean, sugar cane and cotton. In northern Minas Gerais, Cerrado areas are increasingly becoming desertified and more similar to impoverished dry forests because of prolonged droughts, frequent fires and deforestation [60].

## ↑ PANTANAL

A mosaic of periodically flooded marshes, grasslands, savannas and woodlands, by the rivers Paraná and Paraguay in central-western Brazil [68].

**COVERAGE:** 1.8% of the Brazilian territory, continuing into Bolivia, Paraguay, and Argentina [69, 70].

**THREATS**: Despite having 11% of its area protected, the Pantanal faces both erosion and river sedimentation resulting from the transformation into agricultural land [69, 71]. These impacts change the local balance of the flood/dry period characteristic of this biome. The development of hydroelectric plants and urban expansion compromise the delicate balance of local habitats.

## ↑ CAATINGA

Xerophilous thorny forest and scrub of the drylands of north-eastern Brazil.

**COVERAGE:** 9.9% of the Brazilian territory, exclusively Brazilian [65].

**THREATS:** The ongoing habitat degradation and modification in north-eastern Brazil is currently aggravated by desertification, a likely consequence of climate change. Local impacts are caused by mining, fuel-wood extraction, uncontrolled human-induced forest fires and cultivation of cotton [66].

## PAMPA →

Grasslands covering moderate hills and woody groves in southern Brazil.

**COVERAGE:** 2.1% of the Brazilian territory, found also in Argentina, Uruguay, and eastern Paraguay [67].

**THREATS:** Traditionally used for farming cattle, the grasslands of the Pampa have undergone centuries of habitat degradation and selection of species more resilient to grazing conditions. Crop mechanization, specifically soybean cultivation, is progressively replacing such activities. Local disturbances are caused by coal and copper mining, as well as by granite quarrying for roads and buildings.

## ← MATA ATLÂNTICA (ATLANTIC RAINFOREST)

A narrow strip of forest from sea level to the eastern highlands of Brazil, becoming broader toward the south. The largest tracts of surviving Atlantic Rainforest occupy inaccessible terrain near the largest cities of South America.

**COVERAGE:** 13% of the Brazilian territory, and 95% within Brazil [61], extending marginally into Argentina and Uruguay. Only 12% of the original area still remains [62].

**THREATS:** Habitat degradation due to unplanned urbanisation [63], logging, mining and farming. Residues from mining also pose a serious threat to a clean water supply. An extreme example occurred in Mariana in 2015, when a dam collapse resulted in the release of toxic waste into the rivers. This led to human and aquatic death, and to wide-scale destruction. The long-term consequences of this event for local flora and fauna are not fully understood [64].

# CLIMATE CHANGE

## >10%

## OF THE EARTH'S VEGETATED SURFACE DEMONSTRATES HIGH SENSITIVITY TO CLIMATIC VARIABILITY

How is climate change affecting plant species, populations and communities globally? What are some of the climate-smart crops of the future?

https://stateoftheworldsplants.com/climate-change

## IN THE PAST THREE DECADES, CHANGES TO THE CLIMATE HAVE BEEN APPARENT AT A SCALE AND LEVEL OF VARIABILITY NOT SEEN IN THE PAST 850,000 YEARS.

The concentration of global atmospheric carbon dioxide has increased from pre-industrial levels of around 280 ppmv to the current 400 ppmv. Meanwhile, global temperatures at the Earth's surface are warming each year at an average rate that is faster than any trend seen in the past 1,400 years. In many regions, changing precipitation or melting snow and ice are altering hydrological systems and affecting water resources, and some extreme events (e.g. periods of extreme heat) are predicted to increase as temperatures rise [72].

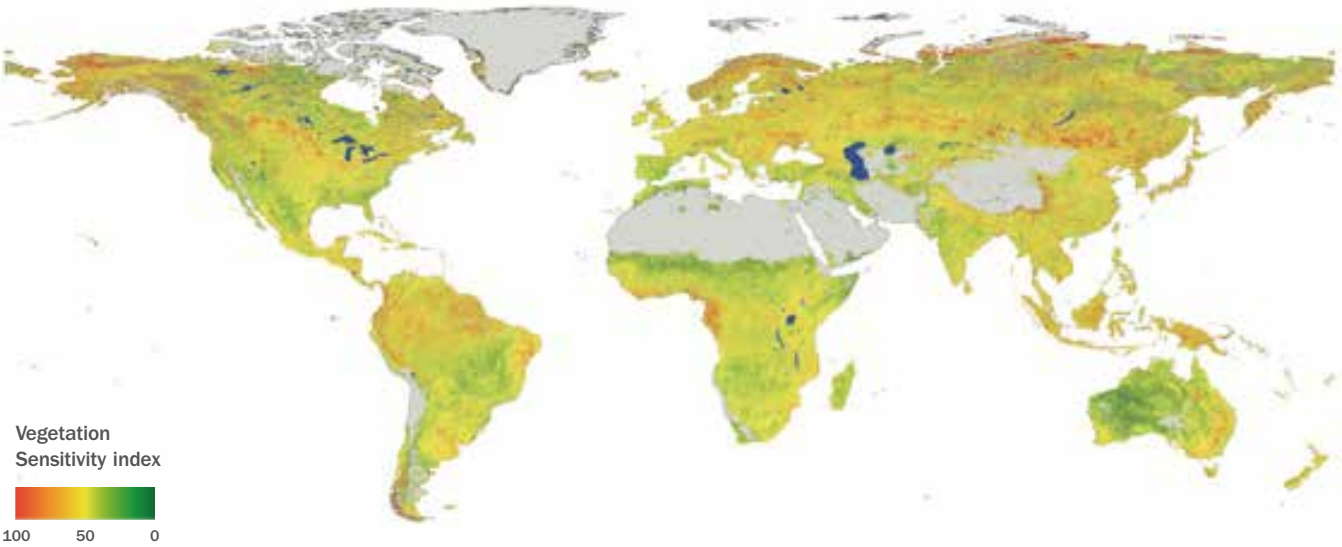
Against this backdrop of changing climates, there is an urgent need to understand the responses of the world's plants to their changing environment at a number of different levels, ranging from genes and species to communities and ecosystems. Broadly speaking, the anticipated impacts of climate change on the world's plants can be classified under three possible outcomes: extinction, migration (in the form of a permanent range shift) or *in situ* adaptation [72–75].

It is not easy to determine that a plant extinction has occurred solely as a result of climate change, and currently there is little published evidence to demonstrate that such extinctions have occurred in the past decade [76]. Nevertheless, based on what is known about plants' environmental tolerances and the predicted climate change by 2050, species-envelope models predict that many plant species may be on 'borrowed time'. These models predict that suitable climate space will become so severely restricted for many species that widespread climate-related extinctions are expected [77, 78]. For many plants (trees in particular), the slow speed at which they can respond, and limitations in local adaptation potential and genetic diversity, also mean that the true impacts of climate change might not be seen for some time [79, 80]. Many plants are predicted to be in a so-called 'extinction debt' already [81, 82]. In addition, climate change will have indirect impacts as the result of changing species interactions, including for example, changes in the distributions and numbers of pollinators and plant pathogens. There is increasing evidence to suggest that these changing interactions are an important cause of documented population declines and potential extinctions related to climate change [76].

The ramifications of loss of suitable climate space, especially for important crops, will have serious economic consequences. In many cases, targeted actions are needed now (see Box 3: Building a Climate Resilient Coffee Economy for Ethiopia, and Box 4: Understanding the crops of the future for Sub-Saharan Africa).

### FIGURE 9: VEGETATION SENSITIVITY INDEX FOR THE INTERVAL 2000–2013

The map displays areas that have shown sensitivity to climate variability over the past 14 years (in red) identified using a vegetation sensitivity index. This index is calculated using time-series data derived from satellite imagery to examine the sensitivity of vegetation productivity at monthly intervals against three climatic variables that drive vegetation productivity (air temperature, water availability and cloud cover). Those areas that have demonstrated a large response to climate variability over the past 14 years are marked in red. In other regions (marked in green), by contrast, there is little change in vegetation productivity, despite climate perturbations. These regions are potentially more resilient to current and future climate change.




SOURCE: SEDDON ET AL. (2016)[98]

Evidence for the latitudinal and altitudinal migration of plants in response to climate changes over the past few decades is apparent in a number of long-term observational studies. In European mountain regions, for example, a study that compared vegetation samples from above the treeline in 2008 with those found in 2001 indicated a significantly higher abundance of thermophilic species (i.e. those requiring warmer temperatures for growth) in 2008 [83]. Thus, at least over this period of time, it would appear that warm-adapted species are migrating up the mountains as the temperatures get warmer, resulting in the loss of cold-adapted species. Similarly, in a study in the western Pyrenees carried out over the past 40 years, significant changes are becoming apparent in the southern-most populations of Scots pine (*Pinus sylvestris*) and European beech (*Fagus sylvatica*) with an increased presence of both in the region. In addition, Scots pine distribution has shifted about 1.5 km northwards and European beech has shifted its distribution southwards by around 2 km. Both species have also extended their altitudinal range upwards by around 200 m [84, 85]. Similarly, in the UK, a study of vascular plant species which compared distributions of plant populations from 1978–1994 with those in 1995–2011 showed a small but significant shift northwards [86].

Observation studies in the USA carried out over the past three decades have also revealed migration shifts. Results from 28 years of satellite imagery of the distribution of mangrove forests on the east coast of Florida, for example, have revealed that these forests have doubled in area at the northern end of their historic range; a change associated with a reduction in the frequency of extreme cold winter events [87]. There are also a number of datasets from Californian and east coast forests that indicate range shifts, population turnover, declining numbers of large trees and increased densities of drought-tolerant trees in some regions [88, 89]. A number of mega-disturbances related to climate change are also apparent, for example, in western North America there have been unprecedentedly large fires, pathogen outbreaks and drought-related plant mortality [90].

Overall, large knowledge gaps exist in our current understanding of range-shifts for terrestrial plants in response to climate change. A recent global multidimensional synthesis, for example, revealed that very little is known about range-shifts in the tropics or lowlands [91].

*In situ* adaptation to climate change depends largely upon a plant's ability to adapt to changing conditions. Sometimes, the response is observable as a change in the plant's phenology (including timing of bud break, first leaf emergence and flowering). Alternatively, a plant's ability to withstand the change might be due to local adaptation, resulting from genetic plasticity and/or morphological traits. A recent review of evidence for local adaptation in plants showed evidence for plastic responses to climate change, indicating local adaptation, in all 29 studies examined (involving more than 50 different plant species) [92]. Changes in the phenology of herbaceous species are also occurring in many regions of the world. For example, an observational study of 1,558 wild plant species from four continents

## BOX 3: BUILDING A CLIMATE RESILIENT COFFEE ECONOMY FOR ETHIOPIA

The global coffee sector has been alert to the likely impact of climate change for at least a decade. In the past three years, these concerns have turned into a stark reality, with drought becoming a major issue in nearly all major coffee-producing countries, including Brazil, the world's principal producer. Despite the immense value of the coffee industry, only a few studies have looked into the long-term impact of climate change in a rigorous scientific manner. In 2013, Kew and Ethiopian partners embarked on the project *Building a Climate Resilient Coffee Economy for Ethiopia* (under the Strategic Climate Institutions Programme), with an aim of providing a strategy based on a detailed assessment of the influence of climate change on coffee-producing areas and wild coffee forests. A multi-disciplinary approach was adopted, including climate profiling and monitoring, computer modelling, high-resolution satellite mapping, rigorous ground-truthing, and surveys of the coffee-farming community. The results of the study show that coffee farming in Ethiopia is likely to be drastically affected by climate change, and that the impact will be location specific. Nevertheless, if appropriate interventions are made, particularly the establishment of new coffee areas at higher elevations, there could be substantial overall gains for coffee farming in Ethiopia that would provide resilience for their coffee sector at least until the end of this century.

### BOX 4: UNDERSTANDING THE CROPS OF THE FUTURE FOR SUB-SAHARAN AFRICA

A recent modelling study looking at different climate scenarios for nine key crops in sub-Saharan Africa has yielded interesting results in relation to the possible crops of the future [99]. The crops examined were banana, cassava, common beans, finger millet, ground nut, pearl millet, sorghum, yam and maize, which between them make up 50% of food production in sub-Saharan Africa. This research is the first of its kind to allocate timeframes for the changes in policy and practice needed to maintain food production and security. Results from this study indicate that six of the nine crops studied look as if they will remain stable under moderate to extreme climate change scenarios. But, up to 30% of areas growing maize and bananas, and up to 60% of those producing beans, are projected to become unviable by the end of the century. Transformation is therefore needed quickly. In some cases, it needs to happen as early as 2025 – less than a decade from now. From the modelling output, it would appear that replacement crops should include root crops (cassava and yams) and drought-resistant cereals (millets and sorghum).

indicated that spring leafing and flowering were advancing at a rate of 5–6 days per 1°C rise in temperature [93].

Impacts of climate change on phenology are also being detected in forests worldwide. In a study of 59 long-term monitoring forest plots located in 24 countries, some with records extending back to 1981, for example, changes in flower production and the overall biomass of trees can be attributed to altered climate patterns [94]. In particular, there has been an increase in flower production, especially of liana flowers in tropical rainforests. An increase in the size of tropical trees is also apparent, with many trees demonstrating faster growth rates and greater sequestration of carbon over the past few decades [95]. Larger size is not necessarily a good thing because the size of tree appears to affect its ability to withstand drought. A worldwide study of forest trees following 40 drought events demonstrated that larger trees suffer most mortality during drought [96].

Another interesting finding from these global forest plots is that environmental variability is the most important factor driving tree population dynamics on decadal timescales [97]. Understanding the sensitivity of global ecosystems to environmental variability is crucial, as this affects all aspects of the ecosystem services that vegetation provides for human wellbeing – from atmospheric regulation through to food security. The relative sensitivity of global ecosystems to climate variability (temperature, precipitation and cloudiness) has therefore recently been assessed using monthly satellite imagery spanning the period February 2000 to December 2013 [98]. Some interesting trends emerged. Firstly, there are significant differences in the main climate drivers for vegetation productivity across the globe. In the tropics, precipitation and cloudiness are the most important climatic drivers of vegetation productivity. In comparison, temperature is the main driver of vegetation productivity from the mid-latitude regions through to the Poles. Secondly, an algorithm to compare the sensitivity of vegetation productivity to variability in the climatic drivers reveals that some regions are more sensitive than others. Ecologically sensitive regions with amplified responses to climate variability include the Arctic tundra, parts of the boreal forest belt, parts of the tropical rainforest, alpine regions worldwide, steppe and prairie regions of central Asia and North and South America, the Caatinga deciduous forest in eastern South America, and eastern areas of Australia (Figure 9).

**ROOT CROPS (CASSAVA AND YAMS) AND DROUGHT-RESISTANT CEREALS (MILLETS AND SORGHUM) ARE THE CLIMATE-SMART CROPS OF THE FUTURE FOR SUB-SAHARAN AFRICA, WHEREAS BANANAS, MAIZE AND BEANS WILL DECLINE [47]**

# GLOBAL LAND-COVER CHANGE

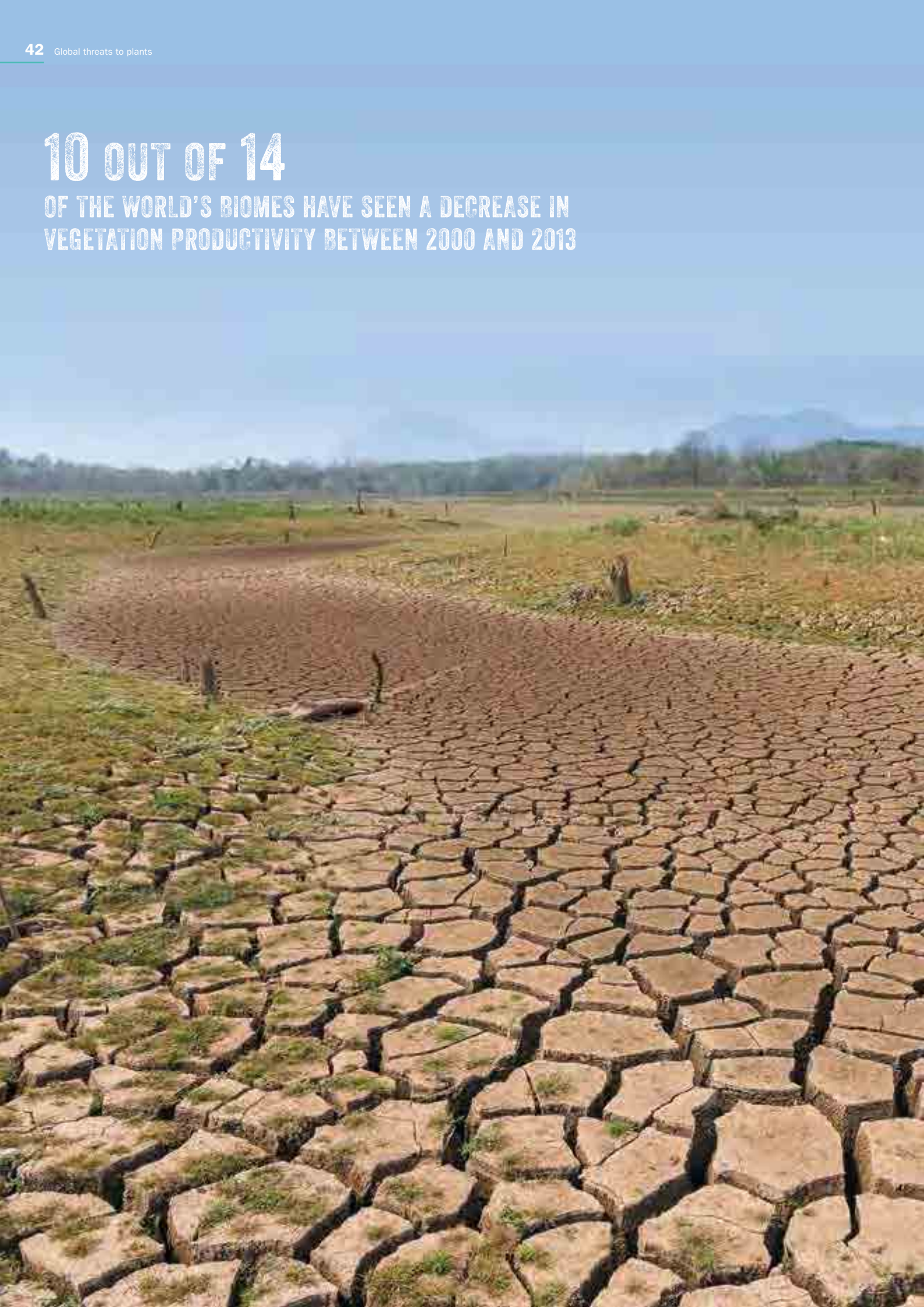
Where in the world are the greatest changes in land-cover type and what are the main drivers of this change? What changes are apparent in vegetation productivity across the globe? Do those regions displaying greatest land-cover change also demonstrate large losses in vegetation productivity?

https://stateoftheworldsplants.com/land-cover-change

False colour composite, Landsat 8 imagery of the Bale and Rift areas Ethiopia. Forest cover is represented by dark red, vegetation cover is light red, bare soils are grey or tan, and clear water is black.

# 10 OUT OF 14

## OF THE WORLD'S BIOMES HAVE SEEN A DECREASE IN VEGETATION PRODUCTIVITY BETWEEN 2000 AND 2013



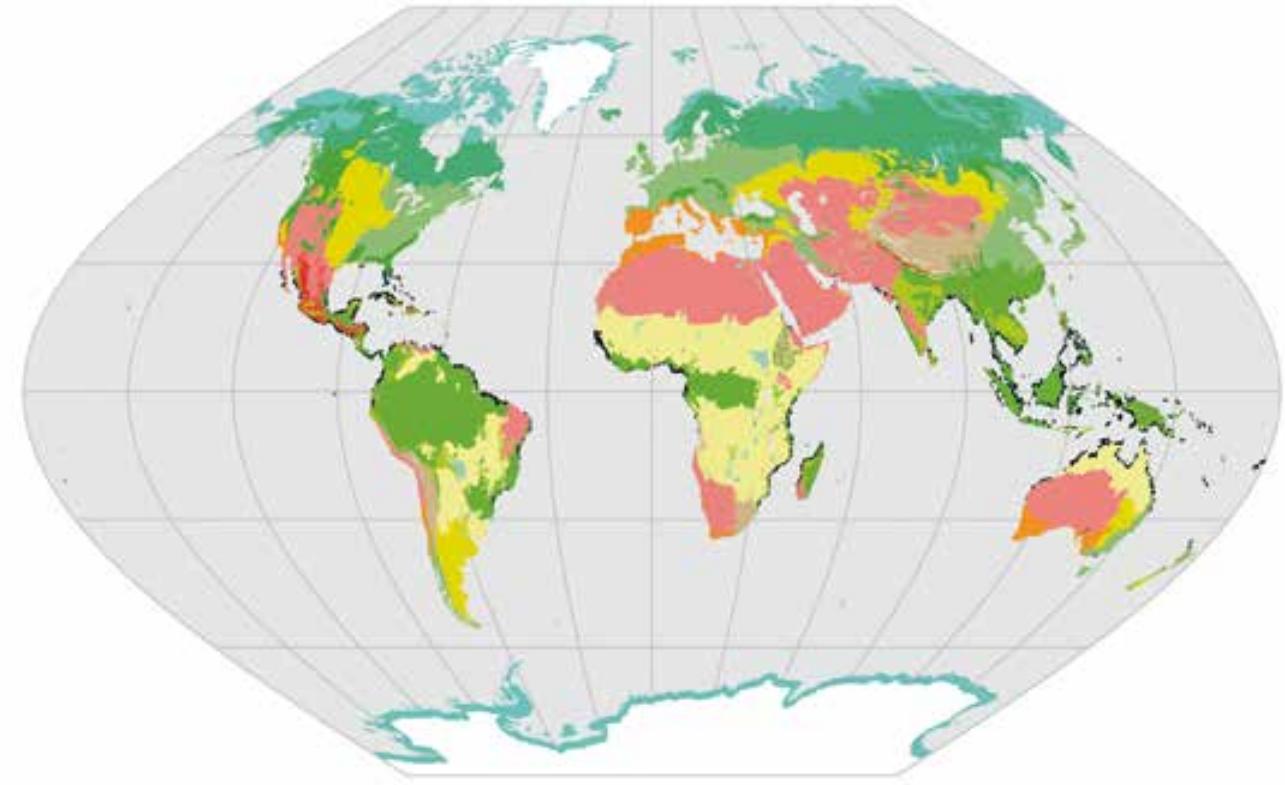
## AT A GLOBAL SCALE, THE WORLD'S VEGETATION CAN BROADLY BE CLASSIFIED INTO 14 'BIOMES'.

These are distinct assemblages of natural communities and species with boundaries that approximate the original extent of natural communities prior to major land-use change [100] (see Figure 10). It is widely acknowledged, however, that significant alterations to these natural biomes have been occurring as a result of climate change and human activity for many decades. A recent re-evaluation of the biomes [100] using satellite imagery, for example, demonstrated that humans have now reshaped more than three quarters of the terrestrial biosphere into anthropogenic biomes (anthromes) [101], and that more than 75% of Earth's ice-free land shows evidence of alteration as a result of human land use [102]. In addition, climate change is having a large impact on many biomes and, in combination with human activity, is bringing about substantial transformation of plant communities.

### BIOMES EXPERIENCING THE GREATEST LAND-COVER CHANGE AND THE DRIVING FACTORS

To examine which global biomes are experiencing the greatest changes in land-cover, and to assess whether the predominant cause is human modification or climate change, we studied a number of existing satellite imagery datasets covering the period between 2001 and 2012. Two measures were used to estimate change in land-cover type. First, we used a satellite imagery product (MOD12C1 collection 5.1 land-cover product; http://landcover.usgs.gov/landcoverdata.php). This product calculates whether each 5 km x 5 km pixel on global satellite images had undergone a change in major land-cover class during the 2001–2012 period or whether the land-cover class has remained the same. The output is a measure of percentage change in each biome from the original to a new land-cover class (see Figure 11a) [103]. The second metric is a measure of vegetation productivity at the same spatial resolution, which uses another MODIS satellite imagery product called enhanced vegetation index (EVI; http://landcover.usgs.gov/landcoverdata.php).

**FIGURE 10: TERRESTRIAL BIOMES OF THE WORLD – AFTER OLSON ET AL. (2001) [100]**



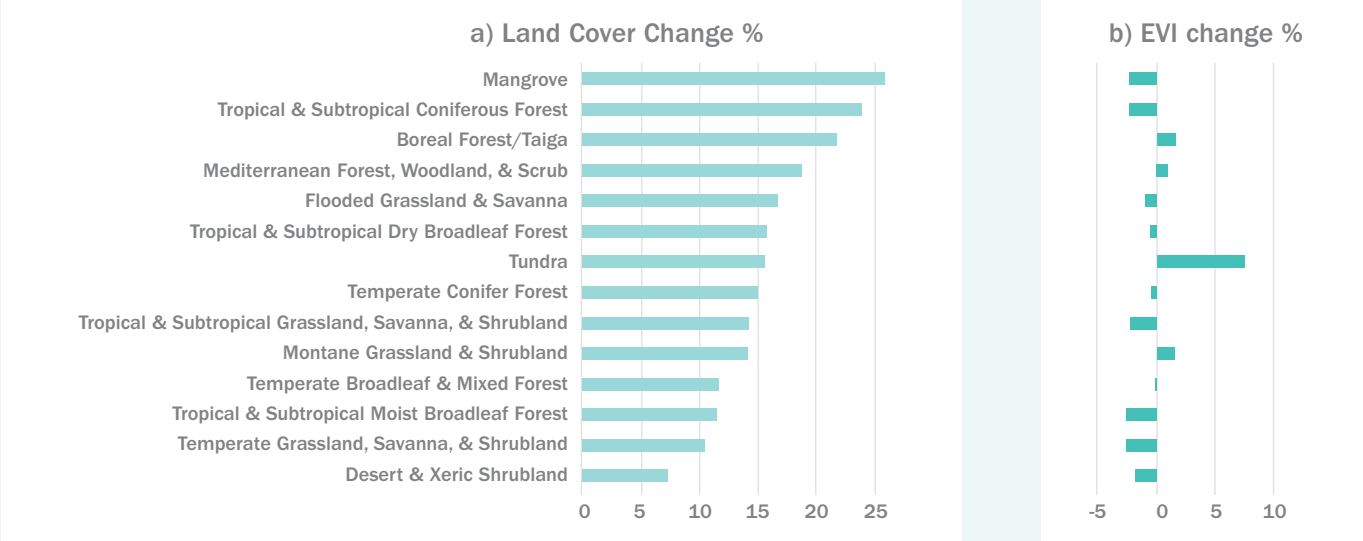
- Mangroves
- Boreal Forests/Taiga
- Deserts and Xeric Shrublands
- Flooded Grasslands and Savannas
- Mediterranean Forests, Woodlands, and Scrub
- Montane Grasslands and Shrublands
- Temperate Broadleaf and Mixed Forests
- Temperate Coniferous Forests
- Temperate Grasslands, Savannas, and Shrublands
- Tropical and Subtropical Coniferous Forests
- Tropical and Subtropical Dry Broadleaf Forests
- Tropical and Subtropical Moist Broadleaf Forests
- Tropical and Subtropical Grasslands, Savannas, and Shrublands
- Tundra
- Rocks and Ice

DATA SOURCE: WWF ECOREGIONS/GIRI ET AL. (2011) *GLOB. ECOL. & BIOGEOG*. 20:154–159

## FIGURE 11: LAND-COVER AND ENHANCED VEGETATION INDEX (EVI) CHANGE

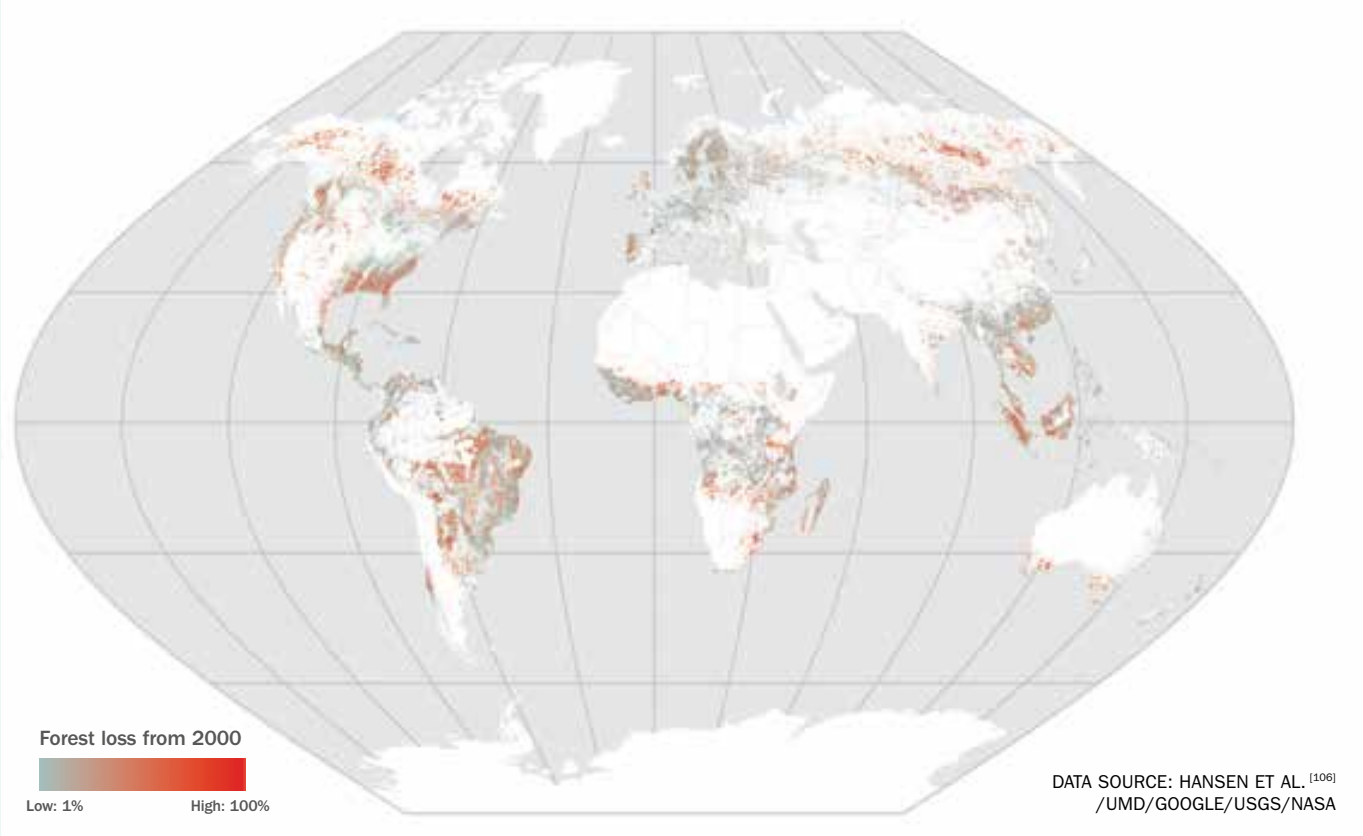
a) Change in land-cover type between 2001 and 2012 as determined using satellite imagery MOD12C1 collection 5.1 land-cover product at a ~5 km resolution globally. The output is displayed as a measure of percentage change in each biome from its original to a new land-cover class during this period.

b) Mean percentage change in vegetation productivity as measured using EVI in each biome between 2000–2004 and 2009–2013.




## FIGURE 12: PERCENTAGE GLOBAL FOREST LOSS BETWEEN 2000 AND 2014

This map shows percentage forest loss across the world where 'red' regions have experienced the most loss. Parts of Canada, Brazil, West Africa, Eastern Russia and South East Asia have experienced the greatest losses in forest cover.



The output is a mean percentage change in vegetation productivity for each biome calculated between the years 2000–2004 and 2009–2013 (see Figure 11b). Change in EVI can occur for a variety of different reasons, including a change in plant structure (e.g. the same plants putting out more leaves), a change in plant community structure (e.g. more shrubs or fewer trees), or an unchanged community experiencing a lengthening or shortening of the growing season. When the EVI output (see Figure 11b) is examined alongside the land-cover data (see Figure 11a), the data from this study concur with previously published data to show some clear trends in global land-cover, and potential drivers of change start to emerge.

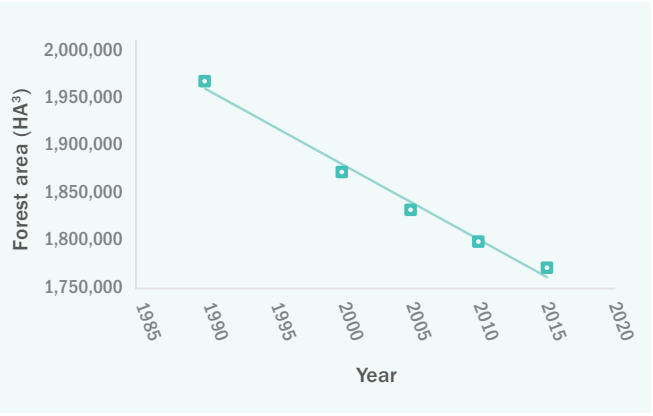
All biomes experienced change in land-cover type between 2000 and 2012, with the proportion of each biome that had undergone land-cover change ranging from 10% to 25%. Perhaps unsurprisingly, the smallest amount of change occurred in temperate grasslands and desert biomes (10% change in land-cover).

The biomes with the greatest land-cover change were mangroves and tropical coniferous forests (see Figure 12). These biomes also have the greatest loss in vegetation productivity over the same interval of time (see Figure 11b), and this change is almost certainly a result of human activities. A number of studies have recently detailed global mangrove loss resulting from human activities, especially conversion of land for shrimp farming. There are some stark statistics relating to loss of mangroves globally; for example, there is evidence that in the past three decades, Indonesia has lost 30% of its mangrove forests with an annual deforestation rate of 1.24% [104]. Equally depressing statistics can be found for many other countries that have mangrove forests, although estimates of loss vary widely [105].

Like the loss of mangrove forests, tropical forest loss is predominantly driven by changes in land use. Globally, tropical forests have lost the most area when compared with subtropical, polar, temperate and boreal forests [106, 107]. Global tropical forest cover has continuously declined over the past 25 years (see Figure 13), with an overall significant decrease in forest area of 9.9% from 1990 to 2015 ($R^2$=0.99) [107] (http://www.fao.org/forest-resources-assessment/explore-data/flude/en/). Conversion of forest to pasture and farmland is a major cause of this deforestation; in particular, clearing forest for oil palm plantations, logging and fibre plantations (pulp and paper) is a severe problem in South East Asia [108]. Deforestation has accelerated in Indonesia, Malaysia, Paraguay, Bolivia, Zambia and Angola over the past 12 years [106]. The deforestation rate in the Brazilian Amazon forest, however, appears to have declined [109]; some encouraging signs are emerging in terms of the increasing amount of tropical forest in Brazil that is afforded some conservation protection status [107].

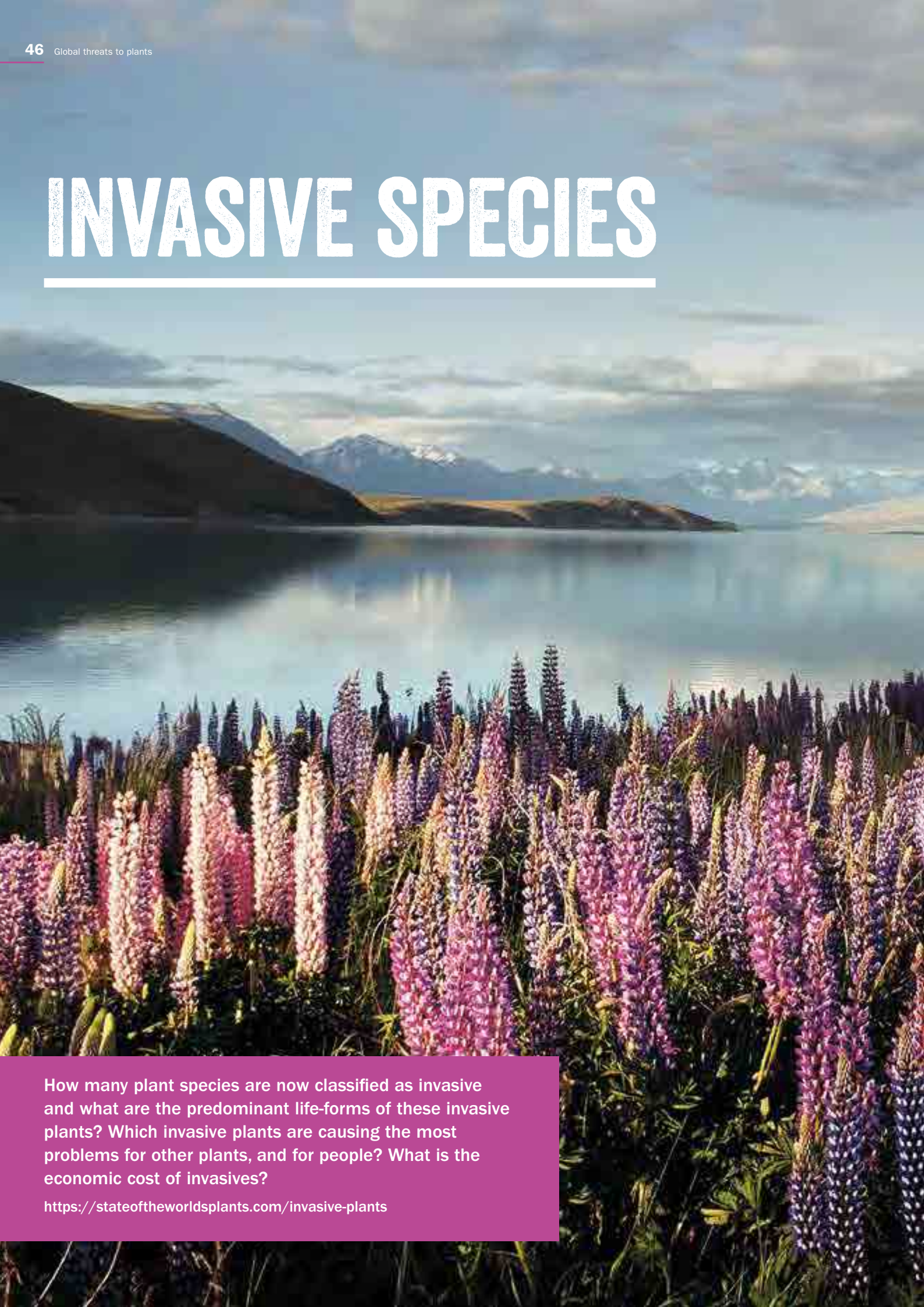
Ten out of the 14 biomes show a decline in vegetation productivity, but four biomes indicate an increase (see Figure 11b). There is increasing evidence that factors related to climate change – namely increases in temperature, precipitation and atmospheric carbon dioxide – are driving the increase in vegetation productivity in these biomes. For example, since the mid-1960s, tall shrub and tree expansion has been seen across much of the Arctic tundra biome [110], including in pan-arctic parts of Eurasia, western North America and eastern North America [111]. This so-called vegetation-greening trend is closely associated with increased warmth in these regions. In the boreal forest of Eurasia, evidence also indicates a climate-driven annual increase in tree growth of 0.3–0.4% since the 1960s; this is probably related to either increasing temperatures or increasing carbon dioxide fertilisation [112].

## FIGURE 13: GLOBAL TROPICAL FOREST AREA 1990–2015




DATA SOURCE: FAO 2015, THE FOREST LAND USE DATA EXPLORER (FLUDE)

# INVASIVE SPECIES



**How many plant species are now classified as invasive and what are the predominant life-forms of these invasive plants? Which invasive plants are causing the most problems for other plants, and for people? What is the economic cost of invasives?**

https://stateoftheworldsplants.com/invasive-plants

# 4,979

## SPECIES ARE NOW DOCUMENTED AS INVASIVE

## HUMANS HAVE BEEN MOVING PLANTS AROUND THE GLOBE FOR CENTURIES, WITH THE RESULT THAT AT LEAST 13,168 SPECIES OF VASCULAR PLANTS ARE KNOWN TO HAVE BECOME NATURALISED OUTSIDE THEIR NATIVE RANGE [113].

Once naturalised plants start to compete with native vegetation and spread to a degree that causes damage to the environment, the human economy or human health, they are known as 'invasives'. As globalisation increases, the number of non-native species will inevitably rise. How many of these will become invasive, and how can we best deal with this escalating threat to biodiversity?

Invasive species are one of the most important drivers of biodiversity loss [114, 115]. Many studies record a reduction of native plant species richness and abundance following invasion [116]. The activity most likely to introduce new invasive species is international trade [117]. Fortunately, most naturalised species do not become invasive. Nevertheless, invasives can cause substantial environmental damage that has socio-economic impacts on livelihoods and on ecosystem services such as agriculture, forestry, water, pollinators and climate regulation [115]. The costs of invasive species have been estimated at nearly 5% of the world economy [118], and their impact on the British economy alone is approximately £1.7 billion every year [119].

Highly invasive Japanese knotweed (*Reynoutria japonica*), introduced as an ornamental plant to Britain in the mid-19th century, costs Great Britain more than £165 million annually to control [119].

Sound taxonomy is essential when documenting invasive alien plant species (IAPS). Taxonomic lists of IAPS exist at local (e.g. Hawai'i Volcanoes National Park [120]), regional (e.g. Gadag District, India [121]), national (e.g. Iceland [122]), continental (e.g. Europe [123]) and global scales. Global lists may focus on a specific plant type – for example 751 invasive trees and shrubs were documented by Rejmánek and Richardson [124, 125]; or on a specific habitat – such as the compilation of 450 IAPS in natural areas by Weber [126]. The Global Invasive Species Database (GISD), compiled by the IUCN Invasive Species Specialist Group [127], records 456 vascular plant species across all life-forms and habitats, while the CAB International (CABI) Invasive Species Compendium (ISC) [128] is the most comprehensive web-based resource with 4,841 vascular plant datasheets [129].

For this report, a synthesis of the ISC [128], GISD [127], Weber (2003) [126] and Rejmánek and Richardson (2013) [124] IAPS global lists was undertaken, with taxonomic reconciliation using Kew databases (The World Checklist of Selected Plant Families and The Plant List). This resulted in a consolidated list of 4,979 invasive vascular plant species. Of these, only 1.6% were reported in all four databases (e.g. *Casuarina equisetifolia*), 4.0% in three of the four, 8.7% in two, and 85.7% in only one reference source (see Figure 14).

The large families Compositae, Poaceae, Leguminosae and Rosaceae contain the most invasive alien plant species (see Table 1), but exceptionally invasive families, containing more than three times the expected number of IAPS, are the Amaranthaceae, Caprifoliaceae, Geraniaceae and

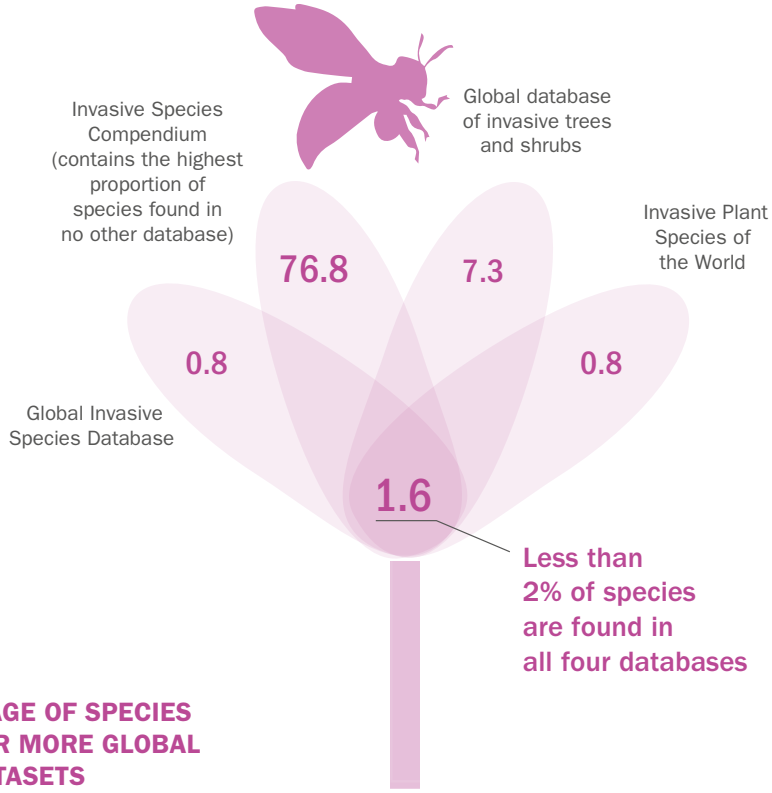



**FIGURE 14: PERCENTAGE OF SPECIES OCCURRING IN ONE OR MORE GLOBAL INVASIVE SPECIES DATASETS**

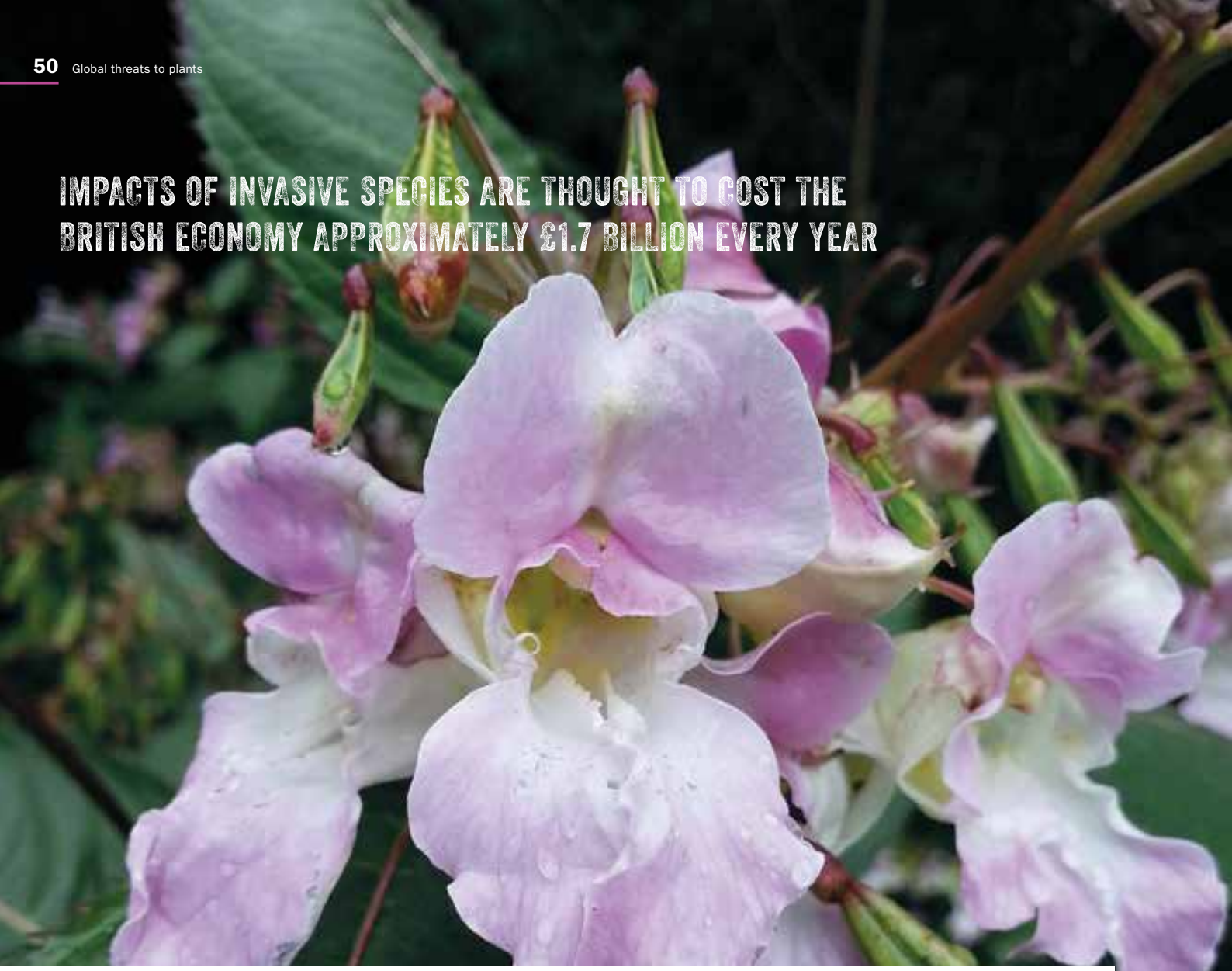
## BOX 5: CASE STUDY: THE BERMUDA CEDAR (*JUNIPERUS BERMUDIANA*)

A dilemma that is increasingly likely to be faced by conservationists is whether to control IAPS that are threatened in their native habitat [141]. For example, *Juniperus bermudiana*, a conifer endemic to Bermuda, experienced a substantial genetic bottleneck following decimation by scale insects that were accidentally introduced onto the island by sailors in 1942 [142, 143]. This species, critically endangered in its native habitat [144], is hybridizing with *J. virginiana*, which was introduced because of its resistance to the scale insects [143]. Prior to this genetic bottleneck, populations of *J. bermudiana* grown from seeds were established for timber on the South Atlantic islands of St Helena and Ascension in the mid-19th century. It is considered invasive on these islands and is currently threatening endemic native species, including *Sporobolus caespitosus* and *Asplenium ascensionis* [127]. The invasive populations of *J. bermudiana* could potentially be used to restore genetic diversity to threatened native populations in Bermuda [142]. The dilemma is whether to protect, control or eradicate *J. bermudiana* in its invasive range.

## BOX 6: CASE STUDY: THE AUSTRALIAN PINE (*CASUARINA EQUISETIFOLIA*)

*Casuarina equisetifolia* is native to South East Asia, northern Australia, Malaysia and Oceania [136]. It is a fast-growing, salt-tolerant pioneer tree species that has become a worldwide invasive problem in habitats with nutrient-poor soils [136, 137]. This species was introduced as an ornamental shade tree and was planted along beaches to stabilise dunes and protect houses against hurricanes in Florida and the Caribbean in the late 1800s. The earliest record of this species from this region held in the Kew herbarium is a specimen collected by Sintenis in Puerto Rico in 1886. Ironically, the shallow roots of *C. equisetifolia* made it unsuitable for coastal stabilisation and protection from weather: in fact it had exactly the opposite effect, promoting coastal erosion following storm damage [138]. The species has rapidly colonised disturbed areas, forming dense stands which inhibit the growth of indigenous flora, reducing suitable habitat for native insects and birds [136], and obstructing the nesting of turtles and the American crocodile [137].

Since 2001, Kew has been mapping the changing distribution of this species in the Turks and Caicos Islands, a UK Overseas Territory and part of the Bahamian archipelago [139, 140]. Understanding its spread and impacts on native coastal flora is helping managers to prioritise and target control efforts, enabling the effective management of this invasive threat and the conservation of native biodiversity.



## IMPACTS OF INVASIVE SPECIES ARE THOUGHT TO COST THE BRITISH ECONOMY APPROXIMATELY £1.7 BILLION EVERY YEAR

### TABLE 1: TOP 10 INVASIVE VASCULAR PLANT FAMILIES FOLLOWING SYNTHESIS AND TAXONOMIC RECONCILIATION

| FAMILY | COMMON NAME | NO. OF SPECIES |
|---|---|---|
| Compositae | Daisy family | 541 |
| Poaceae | Grass family | 528 |
| Leguminosae | Legume family | 391 |
| Rosaceae | Rose family | 239 |
| Brassicaceae | Mustard family | 192 |
| Lamiaceae | Mint family | 135 |
| Amaranthaceae | Amaranth family | 134 |
| Caryophyllaceae | Pink family | 122 |
| Plantaginaceae | Plantain family | 113 |
| Apiaceae | Parsley family | 107 |

### TABLE 2: TOP 15 INVASIVE VASCULAR PLANT SPECIES LISTED IN ORDER OF THE MOST CHEMICAL AND MECHANICAL CONTROL STUDIES CARRIED OUT BETWEEN 1960 AND 2015

| SPECIES | COMMON NAME |
|---|---|
| *Bromus tectorum* | Cheatgrass |
| *Centaurea stoebe* subsp. *maculosa* [a] | Spotted knapweed |
| *Phragmites australis* | Common reed |
| *Phalaris arundinacea* | Reed canarygrass |
| *Pteridium aquilinum* | Western brackenfern |
| *Euphorbia esula** | Leafy spurge |
| *Myriophyllum spicatum* | Eurasian watermilfoil |
| *Tamarix ramosissima** | Saltcedar |
| *Taeniatherum caput medusae* | Medusahead |
| *Microstegium vimineum* | Japanese stiltgrass |
| *Cirsium arvense* | Canada thistle |
| *Bromus inermis* | Smooth brome |
| *Agropyron cristatum* | Crested wheatgrass |
| *Potentilla recta* | Sulphur cinquefoil |
| *Reynoutria japonica* [b]* | Japanese knotweed |

[a] Previously *Centaurea maculosa*
[b] Previously *Fallopia japonica*
* Listed in the Global Invasive Species Databse (GISD) as one of the 100 of the world's worst invasive alien species (Invasion Species Specialist Group (ISSG) [127]).

Onagraceae. Many species within the top three life forms of IAPS – hemicrytophyte, therophyte and cryptophyte – share the ability to die back during unfavourable seasons (see Figure 15). Hemicryptophytes persist as buds on or near the soil surface; cryptophytes as bulbs, rhizomes, tubers or root buds; and therophytes as seeds [129, 130]. The Rejmánek and Richardson (2013) list [124], which is restricted to shrubs and trees, was excluded from taxonomic and life-form analyses, as its inclusion would have skewed the results.

In order to inform conservation action, a means to quantify threats is needed, as the effects of IAPS can vary substantially. In 2010, the European and Mediterranean Plant Protection Organisation (EPPO) published a methodology to enable a list of IAPS that are or could potentially establish in the EPPO region to be produced and prioritised for risk analysis [131]. More recently, Blackburn et al. [132] proposed a classification system for IAPS based on their impact in an environmental context that aligns with the GISD. Their proposed classification scheme is similar to that used by the IUCN Red List. It contains five impact categories ranging from massive to minimal, a category for non-native species whose impact have not yet been determined (data deficient), a category for species not reliably reported to exist beyond their natural range, and a not evaluated category. The adoption of a standardised system to enable communication of the seriousness of threat [132] and would enable appropriate quarantine procedures, early warning systems and control measures to be written into legislation for those IAPS which are likely to have large impacts [133].

Methods for the control of IAPS can be mechanical, chemical, biological, or a combination of these [119]. Kettenring and Adams [134] systematically reviewed IAPS that were the focus of mechanical and chemical control studies between 1960 and 2009, also describing field studies that had quantified the responses of invasive or native plants to control efforts (excluding biological controls, which had been reviewed elsewhere [135]). A subsequent literature survey building on this study [134] identified the 15 IAPS with the most mechanical and chemical control studies (see Table 2). Of these, almost half of the species studied are in the Poaceae.

There is no doubt that despite our best control efforts, IAPS are here to stay. We therefore need to prioritise our actions to best manage the problem. Ideally, this would include closer collaboration between institutions and organisations working with IAPS to enable the establishment of a single global IAPS list that documents taxonomy, threat, distribution, control and other relevant information. Stricter enforcement of legislation and increased implementation of quarantine procedures would minimise the risk of further IAPS introductions and contribute towards Target 10 of the Global Strategy for Plant Conservation (CBD, 2010) [36]. Research efforts should be relevant, scientifically rigorous, and include appropriate controls, with long-term monitoring an essential component to evaluate success. Finally, there is a need for more effective exchange of research findings and practical experiences between scientists and practitioners who are managing natural areas and implementing interventions, to narrow the current wide gap between knowing and doing in this field.

**FIGURE 15: NUMBER OF INVASIVE SPECIES CATEGORISED BY LIFE-FORM***

**HEMICRYPTOPHYTE**

plants with herbaceous stems often dying back during unfavourable seasons, surviving as buds at or just below soil level (biennial and some perennial herbs)

**1,171**

**THEROPHYTE**

annual plants completing their life-cycle during the favourable seasons, surviving the unfavourable season as seed

**1,147**

**CRYPTOPHYTE**

plants with specialised organs (bulbs, rhizomes, tubers, buds), surviving unfavourable seasons underground or underwater

**515**

**CHAMAEPHYTE**

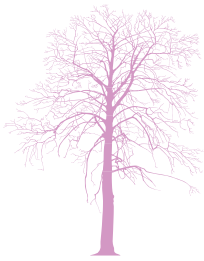
perennial herbaceous or woody plants with buds < 50 cm above ground (dwarf shrubs and some herbs)

**387**

**NANOPHANEROPHYTE**

perennial plants with persistent, woody stems with buds 0.5–3 m above ground (small shrubs)

**360**



**PHANEROPHYTE**

perennial plants with persistent, woody stems with buds > 3 m above ground (trees and large shrubs)

**336**

*Life-form data were only available for a subset of invasive species

# PLANT DISEASES – STATE OF RESEARCH

What diseases pose the biggest threats to plants globally and where is the greatest concentration of research effort on these diseases?

https://stateoftheworldsplants.com/plant-health

COUNTRIES IN

# AFRICA AND CENTRAL AND SOUTH AMERICA

ARE VULNERABLE TO PLANT DISEASE YET ARE CURRENTLY SUBJECT TO LITTLE RESEARCH

## THE TWO BIGGEST THREATS TO PLANT HEALTH ARE PESTS AND DISEASES. HERE WE FOCUS ON PLANT DISEASES, MORE SPECIFICALLY ON THOSE CAUSED BY VIRAL, FUNGAL AND BACTERIAL PATHOGENS.

It is estimated that plant pathogens may account for annual crop yield losses of up to 16% globally [145], and the impact of plant diseases on food security is a major issue [146], especially in parts of sub-Saharan African and the former Soviet Union countries. Over the past 50 years, food crop yields have increased, particularly in regions where access to modern yield-improving F1 cultivars has been greatest [147]. However, crop yield losses to plant diseases have also increased [145, 148]. This may be attributed to human activities in the form of greater trade and travel [149] and to changes in cultivation techniques, which include a tendency to use varieties that provide greater yields but are often more susceptible to diseases [145].

Plant diseases came into focus four years ago with the publication of three papers in the journal *Molecular Plant Pathology* that canvassed a range of experts to generate a list of the top 10 scientifically, historically or economically important viruses [150], bacteria [151] and fungi [152] (see Table 3). Since then, at least one more 'top 10' plant viruses list has been suggested, this time with more focus on a purely economic definition [153].

In order to understand the global research effort relating to these plant pathogens, we asked 'Which of these plant pathogens have been intensively researched in the past 5–6 years and where have these studies focused?' To address this question, we conducted a rapid systematic assessment of the literature for each of the identified 'top 30' plant pathogens in the CABI database (http://www.cabi.org/) between the years 2010 and 2016. This resulted in the assessment of 21,207 publications from 95 countries, of which 10,224 publications were field studies conducted in 160 countries.

### TABLE 3: 'TOP 10' SCIENTIFICALLY, HISTORICALLY OR ECONOMICALLY IMPORTANT VIRUSES, BACTERIA AND FUNGI [150–152] AND THEIR RANK ACCORDING TO RESEARCH EFFORT (AS RECORDED IN RESEARCH PUBLICATIONS) IN THE PAST 6 YEARS.

| | PATHOGEN | NO. OF PUBLICATIONS | RANK | 'TOP 10' RANK |
|---|---|---|---|---|
| PATHOGEN TYPE: VIRUSES | Cucumber Mosaic Virus | 767 | 1 | 4 |
| | Tobacco Mosaic Virus | 603 | 2 | 1 |
| | Potato Virus Y | 571 | 3 | 5 |
| | Tomato Yellow Leaf Curl Virus | 383 | 4 | 3 |
| | Plum Pox Virus | 382 | 5 | 8 |
| | Tomato Spotted Wilt Virus | 376 | 6 | 2 |
| | Cauliflower Mosaic Virus | 282 | 7 | 6 |
| | Citrus Tristeza Virus* | 273 | 8 | 11 |
| | Potato Virus X | 263 | 9 | 10 |
| | Potato Leafroll Virus* | 175 | 10 | 11 |
| | African Cassava Mosaic Virus | 110 | 11 | 7 |
| | Tomato Bushy Stunt Virus* | 89 | 12 | 11 |
| | Cassava Brown Streak Virus* | 66 | 13 | 11 |
| | Brome Mosaic Virus | 44 | 14 | 9 |
| | Barley Yellow Leaf Dwarf Virus* | 0 | 15 | 11 |
| PATHOGEN TYPE: BACTERIA | *Pseudomonas syringae* pathovars | 1,752 | 1 | 1 |
| | *Ralstonia solanacearum* | 1,026 | 2 | 2 |
| | *Xanthomonas oryzae* | 804 | 3 | 4 |
| | *Xanthomonas campestris* pathovars | 699 | 4 | 5 |
| | *Erwinia amylovora* | 632 | 5 | 7 |
| | *Pectobacterium carotovorum* (and *P. atrosepticum*) | 621 | 6 | 10 |
| | *Candidatus Liberibacter* (p.v. *asiaticus*)* | 500 | 7 | 1 |
| | *Xanthomonas axonopodis* | 446 | 8 | 6 |
| | *Agrobacterium tumefaciens* | 432 | 9 | 3 |
| | *Xylella fastidiosa* | 303 | 10 | 8 |
| | *Clavibacter michiganensis* (and *C. sepedonicus*)* | 219 | 11 | 11 |
| | *Pseudomonas savastanoi** | 178 | 12 | 11 |
| | *Dickeya dadantii* (and *D. solani*) | 92 | 13 | 9 |
| PATHOGEN TYPE: FUNGI | *Fusarium oxysporum* | 4,905 | 1 | 5 |
| | *Colletotrichum* | 2,593 | 2 | 8 |
| | *Botrytis cinerea* | 2,485 | 3 | 2 |
| | *Puccinia* (3 species) | 1,173 | 4 | 3 |
| | *Blumeria graminis* | 719 | 5 | 6 |
| | *Fusarium graminearum* | 531 | 6 | 4 |
| | *Magnaporthe oryzae* | 380 | 7 | 1 |
| | *Mycosphaerella graminicola* | 362 | 8 | 7 |
| | *Phakopsora pachyrhizi** | 315 | 9 | 11 |
| | *Ustilago maydis* | 265 | 10 | 9 |
| | *Melampsora lini* | 22 | 11 | 10 |

* Pathogen was not included in 'Top 10' but was identified as just missing out or potentially becoming more important in later years.

## RESEARCH EFFORT ON PLANT DISEASES (2010–2016)

Our findings revealed some interesting trends:

i. The majority (66%) of research into the 'top 10' viral, fungal and bacterial plant diseases was produced by research institutions in only six countries (USA, UK, India, China, The Netherlands and Germany).

ii. The greatest overall research effort in field studies (i.e. excluding purely laboratory-based research) since 2010, accounting for 40% of all studies, was from (in descending order) India, China, USA, Italy, Brazil and Iran. China conducted the highest number of studies on viral plant pathogens (198), whereas India had the most studies on bacterial (286) and fungal plant pathogens (731).

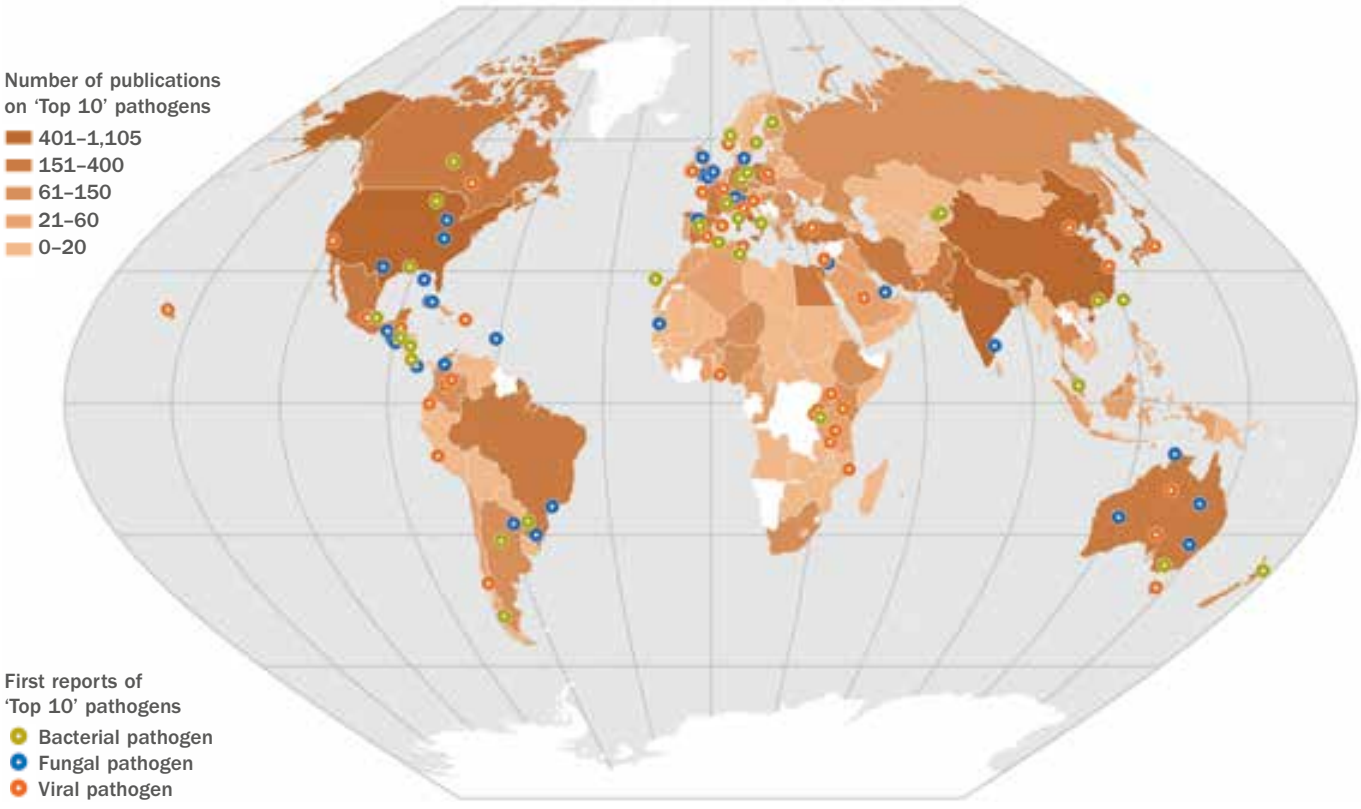
iii. Cucumber Mosaic Virus (CMV) had the highest number of publications of all viruses (767; Table 3). This most likely reflects the broad host range of this virus, which includes economically important vegetables and ornamental plants, and their global distribution [150]. CMV is responsible for major losses of tomato [154], melon, pepper [155, 156] and sunflowers in areas of Iran [157]. In addition, control measures are not very effective [150]; this is stimulating efforts to research the biology of the virus and the control of its vectors.

iv. A high number of publications were concerned with *Pseudomonas syringae*, a bacterial pathogen with many pathovars that affect a wide range of species, with consequences for both food production and the environment [151]. This probably reflects the increasing economic impact of this bacterium, and the impact that mutations, genomic rearrangements and the acquisition of new DNA sequences through horizontal gene transfer are having on its virulence [158]. Other bacterial pathogens that attract a greater number of publications than would be expected from those initially ranked in the 'top 10' include those affecting potatoes, such as *P. atrosepticum* [159], and the alpha-proteobacterium *Candidatus Liberibacter asiaticus*, which is causing increasing losses to the citrus industry [160].

v. Of the fungal pathogens, *Fusarium oxysporum* had the highest number of publications (4,905; see Table 3). Again, this is probably because it causes severe crop losses to a wide range of host species, including melon, tomato, cotton and banana [152, 161]. Two other fungal pathogens causing increased economic loss to major crops were also the subject of a high number of publications: *Colletotrichum*, which is creating major problems for the tea industry [162], and *Botrytis cinerea*, which damages crops such as ginseng in China [163].

### FIGURE 16: MAP ILLUSTRATING WHERE A COUNTRY WAS THE FOCUS OF RESEARCH ON THE 'TOP 10' PLANT DISEASES (SEE TABLE 3) BETWEEN 2010 AND 2016; OVERLAID ON THIS MAP ARE REPORTS OF THE FIRST DETECTION OF THESE PATHOGENS IN-COUNTRY BETWEEN 2010 AND 2015

The darker the colour, the higher the number of publications for that country. SOURCE: BEBBER (2015)[165]



## IS RESEARCH EFFORT LINKED TO THE PLANT DISEASE VULNERABILITY OF A COUNTRY?

The results of a meta-analysis by Bebber et al. [148, 164] showed that there is a positive relationship between a country's ability to monitor and report pests and pathogens accurately and its *per capita* gross domestic product. When these authors removed pests from their analysis, it became apparent that there are fewer reports and publications on pathogens from poorer countries. It is clear that these countries are at a disadvantage, which will impact their ability to evaluate their vulnerability to pathogens.

A further study shows that between 2010 and 2015, 59 countries reported the first occurrence of viral, fungal and bacterial pathogens [165]. Of these, the most reports were from Australia (13) and the USA (9). By contrast, very few African countries reported newly occurring 'top' pathogens. They were the subject of far fewer studies than other countries, despite the fact that they grow many potential hosts. For example, no first reports were recorded for wheat pathogens in Egypt, Morocco, Ethiopia and South Africa, even though wheat production is significant and important in these countries.

Furthermore, analysis showed that even countries with first reports of pathogens were the subject of a low number of publications (Figure 16); for example, Mozambique, Senegal and Burundi had fewer than 11 publications each, Ecuador and Peru fewer than 20 publications each, and countries in Central America fewer than 25 publications each (see also [166]).

Results from our analysis also demonstrate that of the 160 countries contributing to research on the 30 'top' plant pathogens only four African countries were the subject of more than 100 publications since 2010: Kenya (112 publications), Niger (108), Nigeria (104) and Ethiopia (102). Similarly, although many countries in Central America reported at least one of the pathogens, very few of these countries have more than ten publications on the 'top' pathogens. The highest numbers of publications from Central America were found in Cuba (25) and Costa Rica (19). Overall, no scientists from Africa or Central America were among the most active in this field of research.

In summary, research effort into the 30 'top' plant pathogens identified as of high importance to food security predominantly happens in richer countries. Many poorer countries are growing the plants that host and are affected by these pathogens, but are not always contributing to or benefiting directly from this research. Having better monitoring systems in place in poorer countries that involve local scientists, especially in Africa and Central America, would not only provide a better understanding of the global risk of plant pathogens, but would also contribute to our knowledge of the biology of these pathogens in different habitats.

### BOX 7: WHEAT AND SUSCEPTIBILITY TO FUNGAL RUSTS

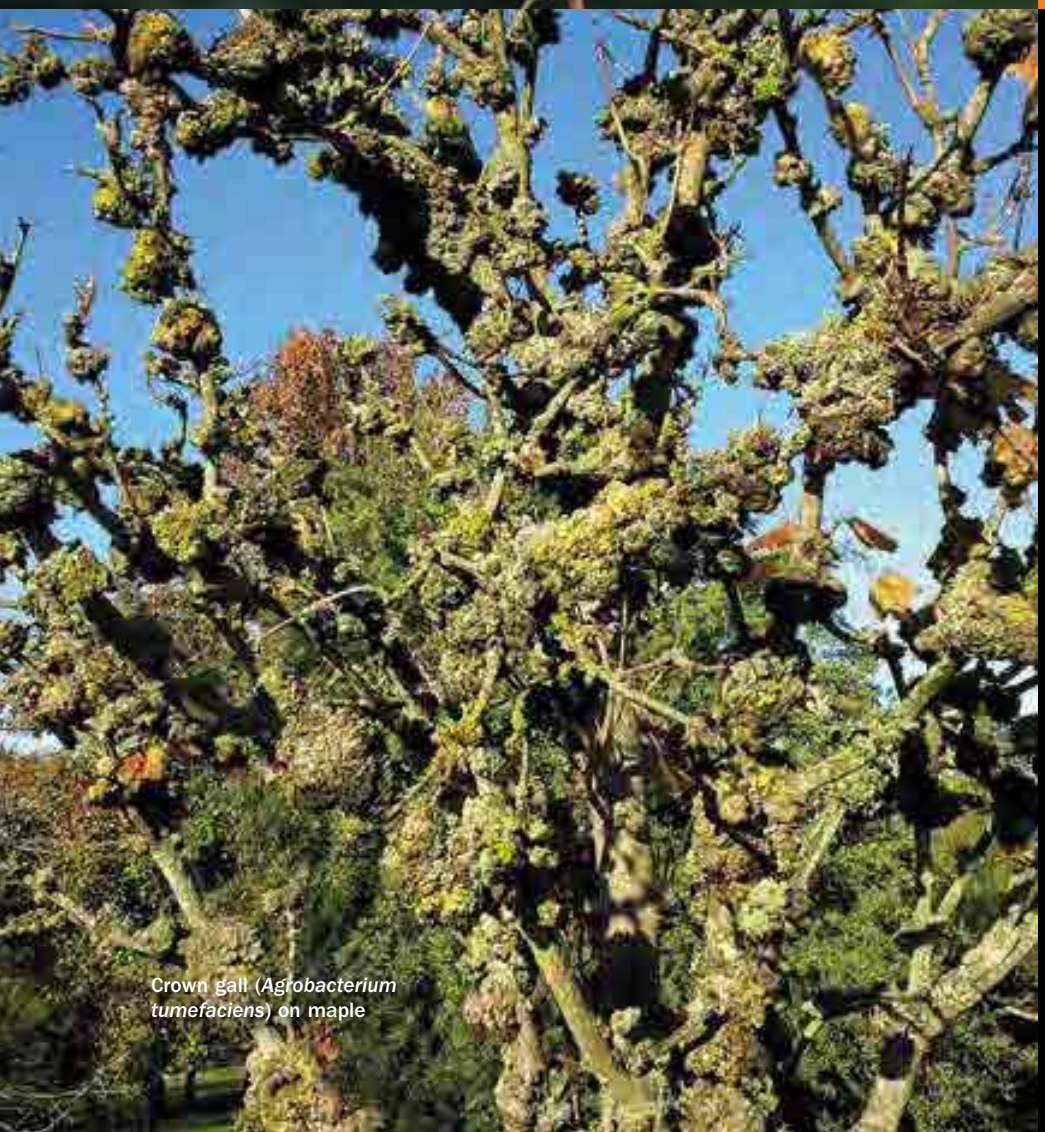
In 2015, UK wheat yields rose by 6%, taking total production to over 16.68 million tonnes with a year-to-year rise in productivity from 8.6 t/ha in 2014 to 9.1 t/ha in 2015 [167]. Despite these encouraging results, there are increasing issues with susceptibility to pathogens that threaten the global wheat market. The main threats are associated with wheat rusts. Many wheat cultivars are attacked by stem (black) rust (*Puccinia graminis* f. sp. *tritici*) (PGT), especially by races such as Ug99 that overcame the resistance of single-gene trait resistant cultivars. Races of PGT have also become more virulent and tolerant of colder climates, whereas races of Yellow Stripe Rust (*Puccinia striiformis* f. sp. *tritici*) (PST), have adapted to warmer temperatures [168]. PST has recently undergone an expansion in its genetic diversity which could significantly influence its virulence [169].

Stem rust (*Puccinia graminis*) on wheat

Cassava Brown Streak Virus on cassava

## BOX 8: VIRAL INFECTIONS IN CROP PLANTS AND ORNAMENTALS

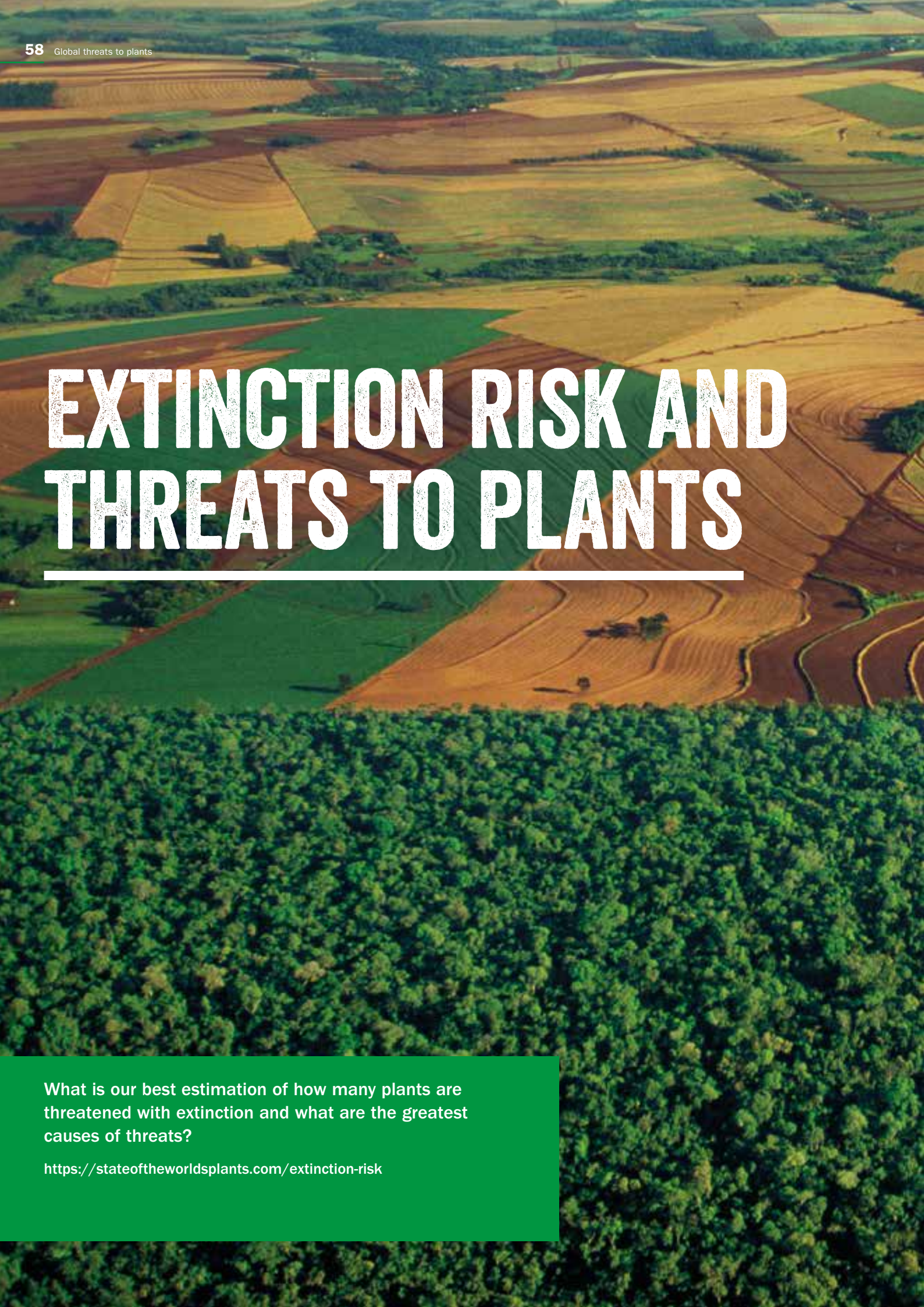
Most crop plants in the UK are susceptible to one or more viral pathogens and these pathogens pose an increasing challenge to plant breeders, especially with the withdrawal of many insecticides that were being used to control their insect vectors. Losses can be high: for example, Barley Yellow Dwarf Virus can cause 80% loss of spring cereals [170], Barley Yellow Dwarf Virus can cause 30–50% loss of barley [171] and Turnip Yellow Virus can result in 10–26% loss in oil seed rape [172].



Crown gall (*Agrobacterium tumefaciens*) on maple

## BOX 9. *AGROBACTERIUM TUMEFACIENS* – A BACTERIAL PATHOGEN

*Agrobacterium tumefaciens* causes crown gall tumours. It triggers growth responses in plants through the transfer of a specific DNA segment known as T-DNA. It is one of the most frequently used bacteria in plant molecular biology [151] and is being used to help propagate economically important plants such as rubber (*Hevea brasiliensis*) [173] and *Jatropha curcas*. It also has a potential use in the propagation of endangered species. Nevertheless, *A. tumefaciens* is still an important pathogen that causes crop loss, as illustrated by its increasing impact on olive trees (*Olea europaea*). It has recently been isolated from the variety 'Chemlali', the most widely grown olive tree cultivar in Tunisia, and is causing damage to olives in Algeria, Jordan, Australia and Argentina [174].



# EXTINCTION RISK AND THREATS TO PLANTS

**What is our best estimation of how many plants are threatened with extinction and what are the greatest causes of threats?**

https://stateoftheworldsplants.com/extinction-risk

# ONE IN FIVE

## PLANTS ARE ESTIMATED TO BE THREATENED WITH EXTINCTION

## EXTINCTION IS AN ABSOLUTE TERM, MEANING THAT NO INDIVIDUAL OF A SPECIES REMAINS ALIVE.

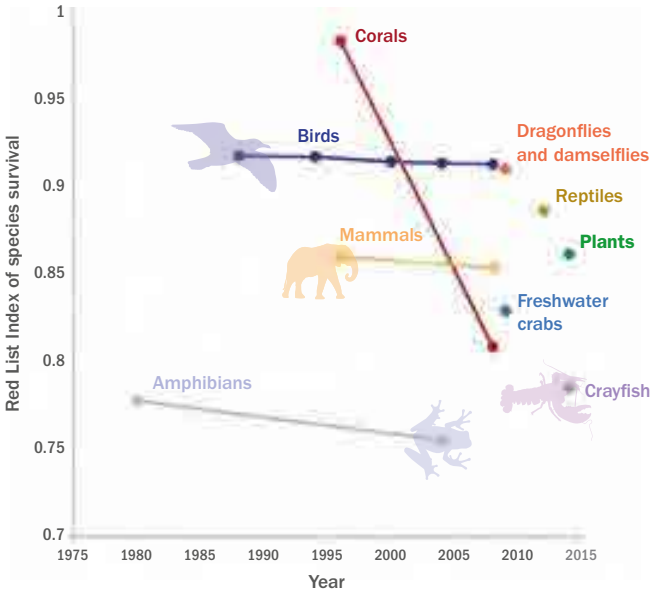
In practice extinction is hard to prove, because a species of plant that appears to be extinct may actually persist in the form of a very small number of individuals. Owing to difficulty in detection of some individuals (such as a rare orchid that only flowers every ten years and is hard to identify when not in flower), or a lack of survey effort (imagine a remote area that is hard to access and has received little attention from botanists), the few remaining individuals of a rare species may remain unobserved and the species recorded as extinct. With concerted effort or a chance finding, these species may be 're-discovered'. In the event of re-discovery, these apparently extinct species are labelled as 'Lazarus' species, touching on the biblical reference to Jesus raising Lazarus from the dead (see Box 10).

The alternative to the binary classification of extinct/extant, is to estimate the probability of extinction so that action can be taken while species decline is still reversible. This is the approach that the *IUCN Red List of Threatened Species* adopts. The Red List collates the work of a large team of specialists from all over the world who assess different groups of organisms, including plants, and score them against quantitative criteria based on parameters such as population reduction and restricted geographic range. These criteria are chosen because they reflect the symptoms of imminent extinction, and, importantly, because they can be estimated from partial or uncertain information. These data are then used to classify a species into a category ranging from extremely high risk of extinction (e.g. Critically Endangered) to little or no risk (e.g. Least Concern). In some cases, there are insufficient data to assess the status, in which case a species is labelled as Data Deficient. The resultant list tells conservationists which species are high risk, low risk, or in need of further investigation. It is a vital resource for conservation. Entire groups of organisms (e.g. birds and mammals) have been assessed in this way. In addition, these extinction risk assessments include documentation of the threatening processes affecting plants (see Figure 19): analysis of the existing Red List of plants shows that the conversion of land for agriculture is the dominant threat, followed by biological resource use.

### A REPRESENTATIVE LIST OF RISK

Over 20,617 assessments of extinction risk for vascular plant species have been carried out and published on the Red List. This represents a quarter of all species on the Red List, but only around 5% of all plants. This small sample is also skewed for various reasons, notably because assessors mostly select species that are likely to be at risk of extinction.

### FIGURE 17: RED LIST INDEX VALUE OF SPECIES SURVIVAL FOR PLANTS IN COMPARISON WITH OTHER GROUPS




A value closer to 1 indicates most species in the group are at low risk, a value towards 0 indicates species that are moving towards extinction. Values for crayfish, freshwater crabs, dragonflies and damselflies, reptiles and plants are based on a sampled approach.

REPRODUCED WITH PERMISSION FROM BRUMMITT ET AL. (2015) [32]

### FIGURE 18: VARIATION IN PUBLISHED ESTIMATES OF THE PERCENTAGE EXTINCTION RISK OF PLANTS

| | % of plants estimated to be at risk | Year of estimate |
|---|---|---|
| | 10% | 1978 |
| | 24% | 1985 |
| | 27% | 1987 |
| | 12.5% | 1998 |
| | 33.33% | 1999 |
| | 15–20% | 2002 |
| | 22–62% | 2002 |
| | 20% | 2008 |
| | 27–33% | 2010 |
| | 20% | 2011 |
| | 30% | 2014 |
| | 27–33% | 2015 |
| | 20% | 2015 |

For a full description of the data sources used please refer to the supplementary material online at: http://stateoftheworldsplants.com/extinction-risk

## BOX 10: BACK FROM THE BRINK? AN EXTINCT IN THE WILD (EW) TREE RE-DISCOVERED

The 'guarajuba', *Terminalia acuminata* (Combretaceae), is a magnificent Brazilian hardwood timber tree, endemic to a narrow patch of Mata Atlantica (Atlantic Forest) in Rio de Janeiro, Brazil. The species was once considered abundant in the surroundings of Brazil's second biggest city and it was first formally described in 1867. The high quality of its timber and vast array of carpentry uses led to relentless over-exploitation, driving the species to the verge of extinction. In fact, it was listed as 'Extinct in the Wild' (EW), with only five living specimens known to exist in the Rio de Janeiro Botanic Garden. In 2015, *T. acuminata* was rediscovered, 80 years after it was last seen in the wild, less than 50 km from the botanic garden. The species is currently assessed as 'Endangered' (EN) by the 'Official National Brazilian Threatened Flora Species List (2014)' (http://cncflora.jbrj.gov.br/portal/static/pdf/portaria_mma_443_2014.pdf) although this assessment will need to be reviewed in the light of new data from ongoing fieldwork. The re-discovery of this enigmatic tree shocked the Brazilian conservation community and represented a significant milestone in the conservation of the Atlantic Rainforest biome.

Analysis carried out for this report reveals that the orchid (Orchidaceae), mint (Lamiaceae) and heather (Ericaceae) families are all under-represented on the Red List. There has been notable recent progress towards the goal of generating a full Red List for all plants [50]. Ambitious plans are underway to tackle major groups of plants such as trees (see Box 11), but sadly the lack of coverage of plants means that the Red List does not yet adequately represent overall extinction risk in plants. We reviewed published estimates of the proportion of plants that are threatened with extinction, which show considerable variation and reflect our uncertainty (see Figure 18).

A solution to a potential bias towards species at high risk is to take a suitably large, random selection of plant species and assess their extinction risk. This representative view of extinction risk in plants has revealed that one in five plant species are estimated to be in the top three 'threatened' categories of Critically Endangered, Endangered or Vulnerable [32]. Further assessments of the sample in future years will establish an overall trend in the extinction risk index for plants.

## WHAT NEXT FOR EXTINCTION RISK ASSESSMENTS?

Clearly there is a need to expand the coverage of threat assessments and to speed up the process of assigning plant species an extinction risk rating, while ensuring scientific rigour [175]. Promising advances in the field of Earth Observations, including the opening up of global datasets with long-time series (such as maps of forest loss), will enable more quantitative analysis to support assessments, in particular declines over time [106, 176, 177]. The increase in digitisation of specimen data from the world's herbaria, and access to global species-occurrence data through services such as the Global Biodiversity Information Facility (http://www.gbif.org), has also meant that analysis can be based on a more complete knowledge of observation records over time and can allow the use of statistical models to estimate population declines [178] (see Figure 17). These methods have further potential to detect trends in species populations when combined with the scalability of opportunistic data from citizen science initiatives [179]. In summary, there is an urgent need to gain a more thorough understanding of which plants are threatened and where, so that conservation initiatives can be effective and plants can be saved well before they become candidates for extinction.

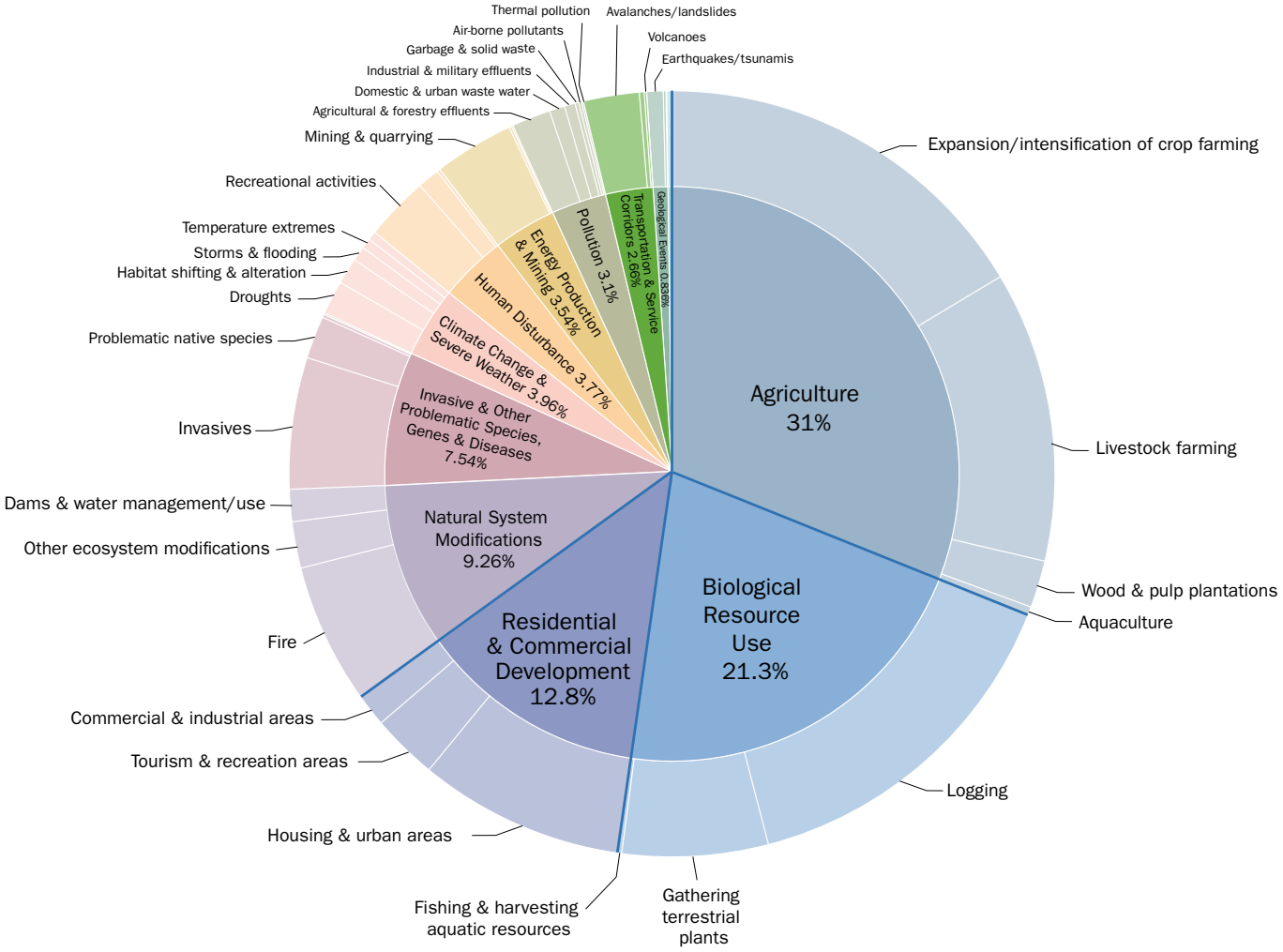
### BOX 11: GLOBAL ASSESSMENT OF ALL TREES

Trees are an essential component of plant diversity, underpinning ecosystems and supporting livelihoods. Ongoing forest loss is threatening the world's trees, but an important new initiative, the 'Global Tree Assessment', has set a target of undertaking conservation assessments for all of the world's tree species by 2020 in order to prioritise conservation actions. Progress has already been made with several groups, including birch, magnolia, oak and maple, and there is a regional focus on the trees of Central Asia, the Mexican Cloud Forest and the Tropical Andes. Work is presently underway on timber trees, the trees of Europe and the Red List of Theaceae – the family which includes the tea plant, *Camellia sinensis*. Theaceae also includes some economically important timbers and ornamental species.

In conjunction with activity on Red List assessments of tree species, efforts are underway to collect and safely store the seeds of threatened trees. The Global Tree Seed Project aims to collect the seed of 3,000 of the world's most threatened tree species for long-term conservation in Kew's Millennium Seed Bank.

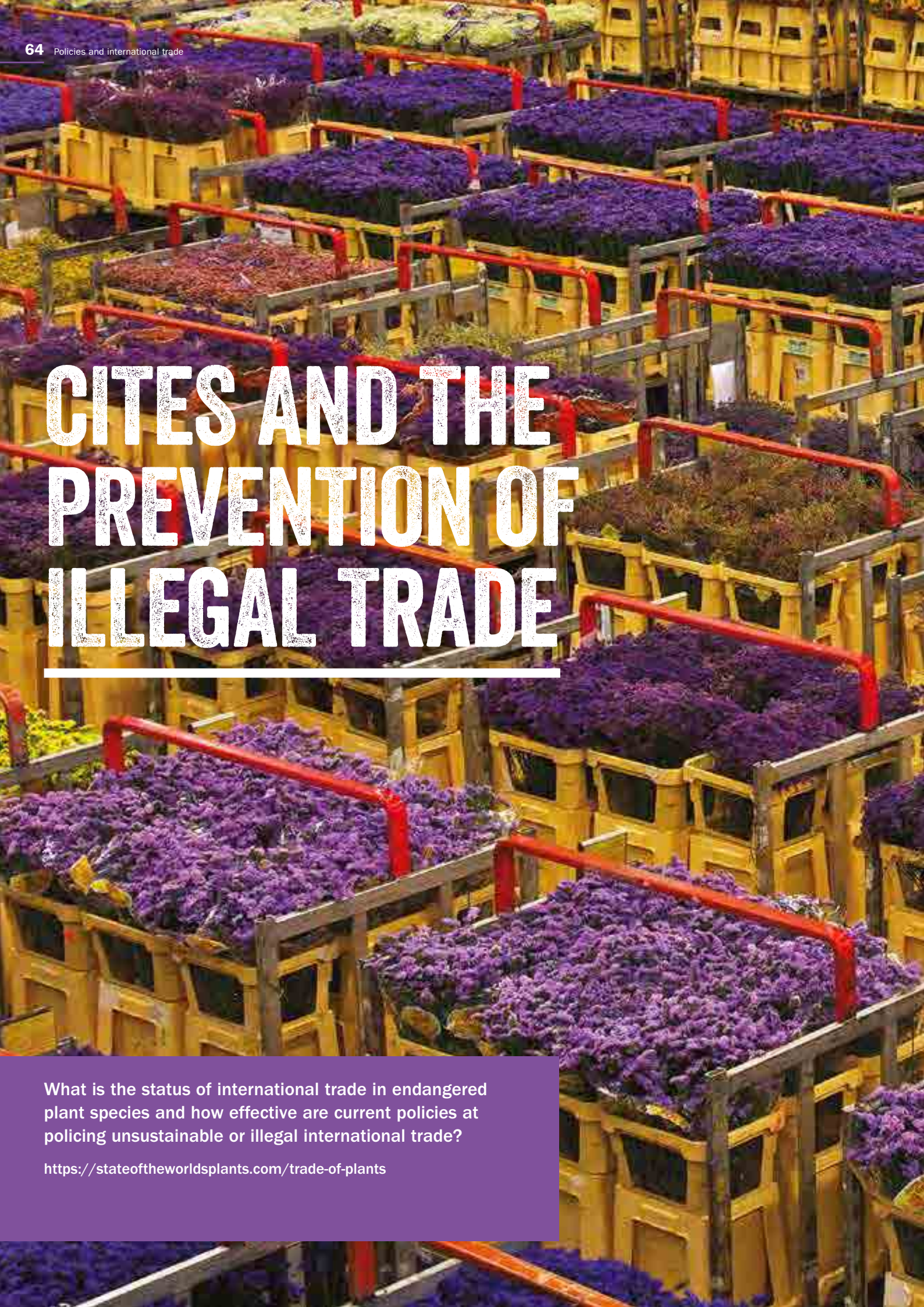
**https://www.bgci.org/plant-conservation/globaltreeassessment/**
**http://science.kew.org/strategic-output/banking-worlds-seeds**

## FIGURE 19: SUNBURST DIAGRAM SHOWING BREAKDOWN OF THREATENING PROCESSES FOR VASCULAR PLANT SPECIES ASSESSED ON THE IUCN RED LIST




The first level of threat classification is shown in the inner circle with percentage of species subject to each threat. The outer ring shows the second level of threat. Threat classification is modified from the IUCN-CMP Unified Classification of Direct Threats. (See website for enhanced interactive version of these data: https://stateoftheworldsplants.com/extinction-risk)

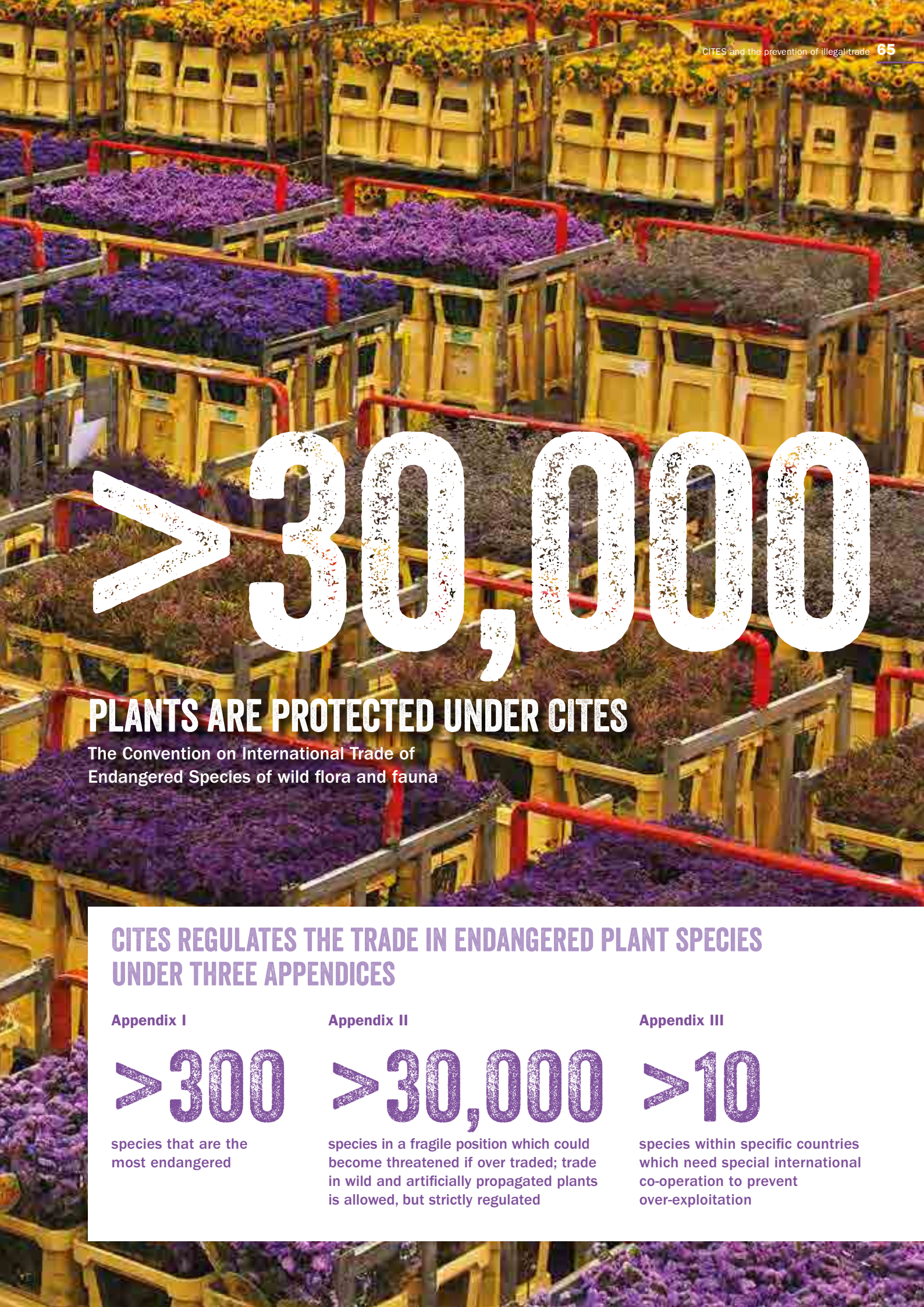
**OVER 20,617 ASSESSMENTS OF EXTINCTION RISK FOR VASCULAR PLANT SPECIES HAVE BEEN CARRIED OUT AND PUBLISHED ON THE IUCN RED LIST, BUT THIS ONLY REPRESENTS AROUND 5% OF ALL VASCULAR PLANTS**



# CITES AND THE PREVENTION OF ILLEGAL TRADE

What is the status of international trade in endangered plant species and how effective are current policies at policing unsustainable or illegal international trade?

https://stateoftheworldsplants.com/trade-of-plants



# >30,000

## PLANTS ARE PROTECTED UNDER CITES

The Convention on International Trade of Endangered Species of wild flora and fauna

## CITES REGULATES THE TRADE IN ENDANGERED PLANT SPECIES UNDER THREE APPENDICES

**Appendix I**

**>300**

species that are the most endangered

**Appendix II**

**>30,000**

species in a fragile position which could become threatened if over traded; trade in wild and artificially propagated plants is allowed, but strictly regulated

**Appendix III**

**>10**

species within specific countries which need special international co-operation to prevent over-exploitation

## BOX 12: ROSEWOODS

A huge increase in demand for luxury timber items for furniture and musical instruments in newly developing economies has led to increased demands for rosewood, a range of tree genera and species with attractive red hues and veined timber. Currently there are 58 species of the more common rosewood genus listed on CITES, *Dalbergia* [180]. The increasing international demand for rosewood is driving systematic illegal logging across Africa and Madagascar, Asia, and North and South America. In West Africa, rosewoods have been termed 'blood timbers' owing to the trade's connections with illegal wildlife trafficking and rebel groups [181]. The identification of different species of *Dalbergia* to aid enforcement of listings is crucial to this process [182, 183]. Recently, a chemical compound new to science and unique to Brazilian rosewood (*Dalbergia nigra*) was discovered and named dalnigrin [184]. This compound has great potential for use as an identification tool to determine illegal trade in this timber.

## INTERNATIONAL TRADE IN PLANTS PLAYS A MAJOR ROLE IN THE GLOBAL ECONOMY AND IS DOMINATED BY THE AGRICULTURE, HORTICULTURE AND TIMBER INDUSTRIES.

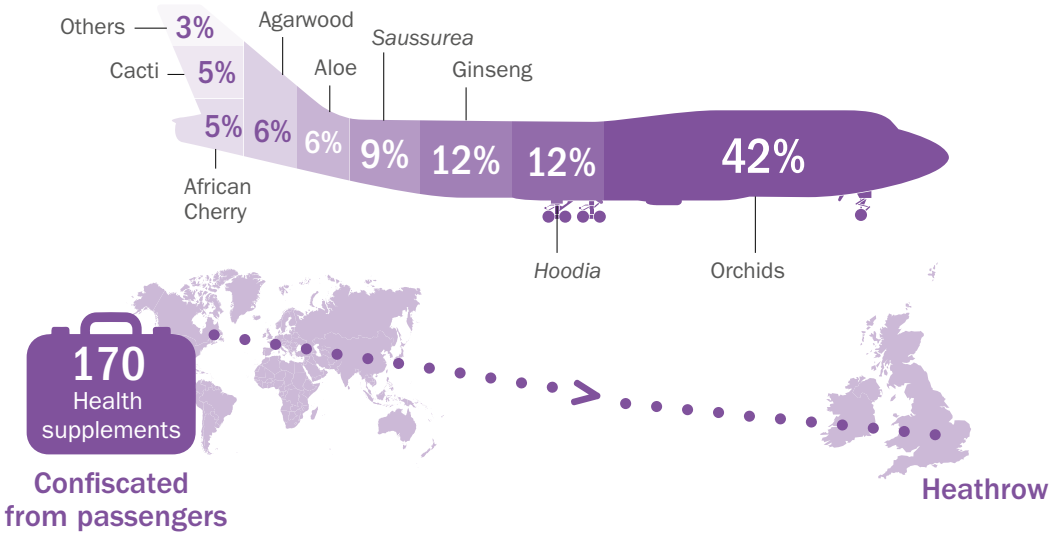
Since the world's population reached 7.3 billion, newly developing and populous countries are playing an increasing role in the global economy and international trade [185].

Agriculture is currently estimated to be worth around US$5 trillion per year and this figure is increasing [186]. Agricultural production also uses around 40% of the world's land, and global trade is a major determinant of agricultural expansion [187]. The growing international trade in palm oil during the past 20 years, for example, has had significant effects on the conversion of natural forest and peatlands to palm oil plantations, with associated impacts on biodiversity [188]. Although the majority of globally traded timber is from plantations, most timber from the tropics is harvested from natural forests. Around US$80 billion worth of primary tropical timber products were imported globally in 2014 [189]. Agriculture expansion and the destruction of tropical forests threaten the survival of many species, and degradation of habitat was identified as the main threat to 85% of the threatened species on the IUCN Red List [190].

The horticulture industry was worth US$16bn in 2015 [191]. This industry relies mainly on artificial propagation, but there is much demand for wild rare species [192,193]. Recent examples include Asian slipper orchids, where 99% of species are threatened with extinction because of wild collection to fulfil horticultural demand [194]. The internet trade and social media are also playing a large role in widening the horticultural market, especially for rare and unusual species. These plants can fetch high prices and fuel unsustainable local harvesting, forcing many species to the brink of extinction [192, 193, 196].

The increasing demands from international trade, which threaten the survival of so many species in the wild, were first recognised in 1975 when the Convention on International Trade in Endangered Species of wild fauna and flora (CITES) came into force [196]. A total of 181 countries, or Parties, have now signed up to CITES, committing to protect 29,905 plant species from unsustainable or illegal international trade [197]. Species are listed in one of three Appendices (I, II and III), which afford varying degrees of protection. The import, export and re-export of both wild and cultivated plants and of their parts and derivatives are regulated by a CITES permitting system. Each Party must designate a Management Authority to administer the licensing or permitting system and a Scientific Authority to advise them

### FIGURE 20: SIMPLIFIED DIAGRAM ILLUSTRATING HEATHROW AIRPORT DATA ON ILLEGAL PLANT CONFISCATIONS IN 2015




The total number of plant seizures at Heathrow in 2015 was 385, consisting of 287 health supplements or Traditional Asian Medicines, 46 live plants, 26 plant parts and derivatives, and 26 timber or wood products. The largest amount of seized materials contained orchids (42%), mainly in the form of health supplements. These supplements came mainly from the US (170) and contained orchid species of Asian origin, showing the complexity of illegal trade routes. The other plant materials confiscated included *Hoodia* (12%), ginseng (12%), *Saussurea* (9%), agarwood (6%), *Aloe* (6%), cacti (5%), African cherry (5%) and others (3%) (consisting of rosewood, Bromeliads, goldenseal, euphorbs and aroids).

287 health supplements
46 live plants
26 parts or derivatives of plants
26 timber or wood products

## BOX 13: SNOWDROPS

One of the most popular garden plants in the UK, the snowdrop (*Galanthus*), was listed on Appendix II of CITES in 1990, allowing international trade that does not detrimentally impact the survival of wild populations. Since the 1990s, CITES Parties expressed concern about the sustainability of exports of one species, *Galanthus woronowii*, from Georgia. In 2009, a project was set up to assess the status of wild and cultivated populations, which concluded that an annual harvest and export quota of 15 million bulbs per year from the wild was probably not detrimental to the survival of wild populations [199]. Research is now underway to establish a monitoring system to continually assess the status of the wild and cultivated populations and to establish opportunities for more small stakeholders to participate in the trade, thereby supporting local livelihoods.

on the effects of trade on the conservation status of the species. Kew has been the UK's CITES Scientific Authority for flora since the UK signed up to the Convention in 1976. It advises the UK government on CITES-related scientific matters, including whether trade in a species is sustainable (see recent examples in Boxes 12 and 13).

One of the main plant groups that are widely traded, and the group that dominates the CITES appendices, are orchids (around 30,000 species: see Givnish et al. [198] and http://www.emonocot.org). The main purpose of reported trade in orchids is commercial, with a small amount of trade in specimens for scientific purposes (see [196]). There is, however, an increasing body of evidence that many species are being traded across international borders in the absence of CITES permits [200]. Trade in orchid flours, made from ground-up orchid tubers, has been restricted to parts of Africa and Asia for many years [201, 202]. This trade has now expanded to reach global markets (Gardiner & Smyth, pers. obs.). In Zambia and neighbouring countries, the traditional delicacy chikanda, made from ground orchid tubers and peanut flour, has been eaten for many decades. Most of the species harvested for chikanda production are members of the genera *Disa, Satyrium* and *Habenaria*. In Zambia, the depletion of native orchids has led to the sourcing of orchid tubers from other countries, including Tanzania, Angola, Democratic Republic of Congo and Malawi. It has been estimated that between two and four million orchid tubers are being exported from Tanzania to Zambia every year [201]. Turkey is the main harvester and producer of salep flour, but more recently, harvesting of tubers from Iran, Pakistan and India has been reported as the result of increasing demand. It was estimated that 7–11 million orchids, representing 19 species and subspecies in seven genera, were harvested in Iran in 2013 for salep production [202]. Growing interest in artisanal and wheat-free flours has seen the import of salep into many parts of the UK and European Union. All of this trade is illegal (Gardiner & Smyth, pers. obs.).

Many orchid species are also commercially traded as ingredients in the products we buy from supermarkets, health stores and pharmacies. A recent study found 39 species of orchid in European commerce in one form or another [203]. Evidence is emerging that many nutritional supplements contain orchid species that may not be legally sourced [203]. Significant quantities of a variety of supplements containing orchid (especially *Dendrobium* spp.) have been seized recently by UK Border Force. Researchers face a great challenge in seeking to identify individual species in compound products such as flours, health supplements and cosmetics.

## HOW SUCCESSFUL IS CITES IN PREVENTING ILLEGAL TRADE?

It is difficult to find accurate data relating to illegal trade in plants as most of the undocumented illegal trade is 'invisible' [204]. As a snapshot of the illegal trade in plants in the UK, we obtained the 2015 data on seizures at Heathrow airport (see Figure 20), the world's busiest international airport with over 1,000 flights a day (http://www.heathrow.com). Live plants, plant derivatives and timber derivatives make up over half of the total seizures made by UK Border Force officers at Heathrow (G. Clarke, pers. comm.). Of the total of 385 plant and plant derivative items seized in 2015, 74% were health supplements that were classified as Traditional Asian Medicines, 12% live plants, 7% plant derivatives (cosmetics) and 7% timber derivatives. The health supplements, live plants and plant derivatives that were seized were dominated by individuals or parts of the orchid family, which are all protected under CITES legislation. The health supplements were derived mainly from Asian *Dendrobium* species, with no indication as to whether the source material for such products was from the wild or from artificial propagation. The seizures in timber derivatives were mainly agarwood, the fungal-infected resinous heartwood of *Aquilaria* and *Gyrinops* species used in fragrances: all species in these two genera are listed under CITES [180]. These data demonstrate the desirability of orchids in all forms and support the need to retain the orchid family in the CITES appendices. The current emerging issue from these data is the lack of traceability of orchid products once they have been harvested and transposed into manufactured medicinal supplements and cosmetics. The increasing globalisation of trade, which means that the source and manufacture of CITES-listed plant-derived products can be many continents apart, is a real issue: CITES enforcement needs to be robust and standardised around the world in order to curb the huge trade in illegal wildlife trafficking (of plants and animals), currently estimated to be worth between EUR 8–20 billion each year [181].

AROUND US$80 BILLION WORTH OF PRIMARY TROPICAL TIMBER PRODUCTS WERE IMPORTED GLOBALLY IN 2014

# THE NAGOYA PROTOCOL ON ACCESS TO GENETIC RESOURCES AND BENEFIT SHARING

Many countries have now ratified the Nagoya Protocol on Access and Benefit Sharing. What are the early signs of its effectiveness?

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# 74 PARTIES TO THE NAGOYA PROTOCOL

## WITH 74 PARTIES, INCLUDING THE UK, THE NAGOYA PROTOCOL IS SET TO CHANGE THE WAY GENETIC RESOURCES ARE COLLECTED AND SHARED.

The concept of fair and equitable benefit sharing from the use of genetic resources – one of the major pillars of the 1993 Convention on Biological Diversity (CBD) (http://www.cbd.int) – has proved tough to pin down and implement [205, 206]. Countries are increasingly recognising the wealth of their natural capital and, through rapid technological advances, are discovering new uses of and benefits from biodiversity (such as the use of microorganisms to speed up industrial processes, improvements in DNA-sequencing techniques, or enhanced trait selection to develop, for instance, climate resilience in seeds) [207]. At the same time, they are struggling to ensure that citizens benefit from the use of their natural resources, and that benefits (in the form of both money and research capacity) support long-term conservation and sustainable use [208]. Concerns about the unauthorised use of biological resources and information highlight the importance of accurately documenting and disseminating the use of genetic resources and traditional knowledge (Boxes 15 and 16). This has presented a huge challenge to biodiverse developing countries that are anxious to harness revenue and capacity from their resources [209], but are struggling with legislation that relies on physical access to resources as the trigger to negotiate benefit sharing (Bern Declaration, 2013).

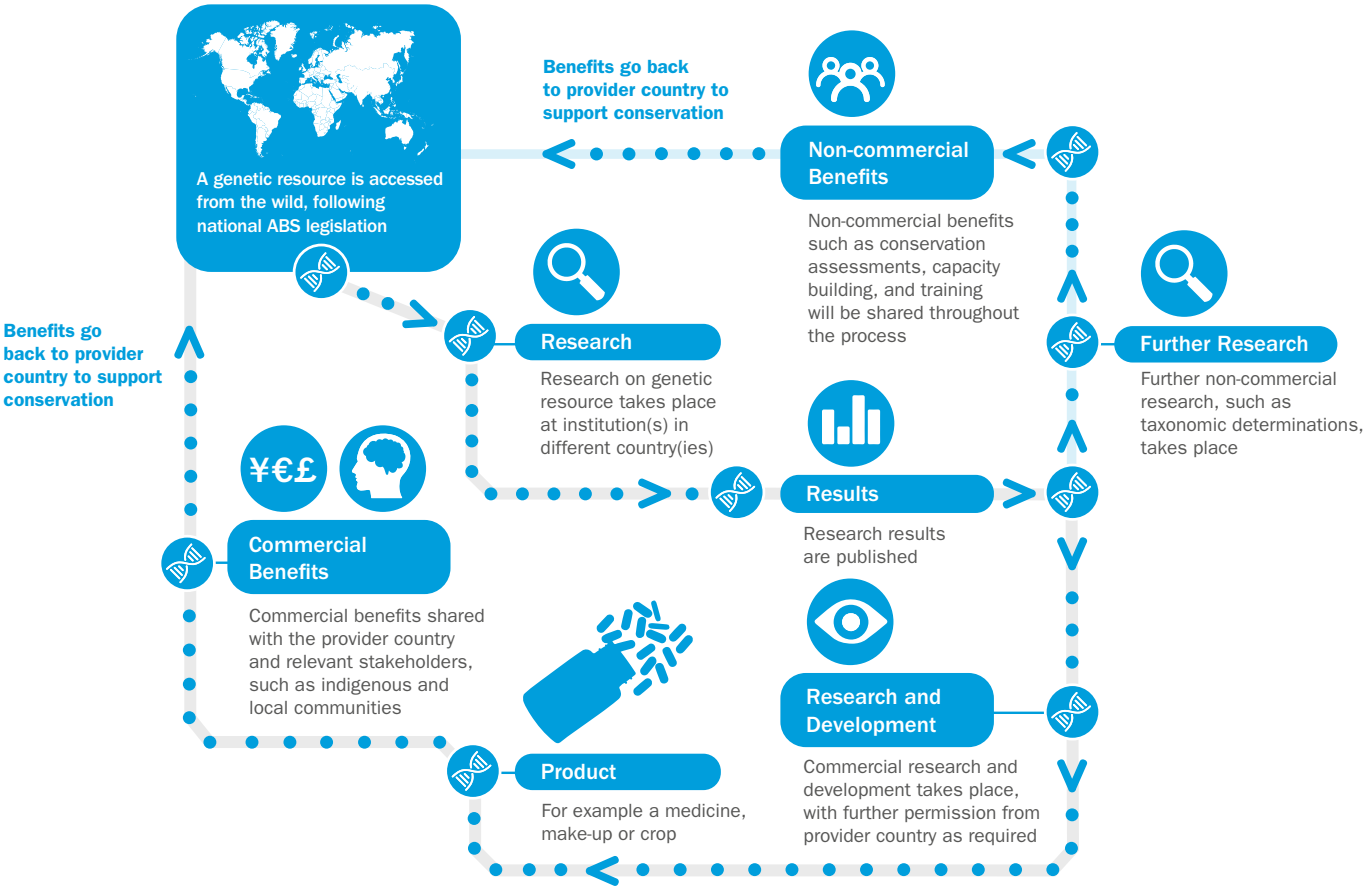
Consequently, the Nagoya Protocol on Access to Genetic Resources and Benefit Sharing (The Nagoya Protocol) was negotiated under the auspices of the CBD and came into force on 12 October 2014 (http://www.cbd.int/abs). It is a legally binding instrument requiring Parties to put national measures in place to ensure that resources exploited in their jurisdiction have been legally acquired, and that benefits from their use – ranging from financial to vital conservation knowledge – are shared. Parties also need to have measures, such as checkpoints, in place to monitor how resources are used and, crucially, to take action to punish instances of non-compliance [210]. (See Figure 22 for a simplified view of how access and benefit-sharing might work.)

### ARE THINGS CHANGING?

Leading up to the Protocol's adoption, many countries introduced a range of national mechanisms to ensure that they could better monitor whether genetic resources were being legally used. These have included: (i) introducing checkpoints in patent applications to require disclosure of origin (used for example by Brazil, India and Norway); (ii) establishing digital resources to record traditional

**FIGURE 21: PARTIES TO THE CONVENTION ON BIOLOGICAL DIVERSITY (CBD) AND NAGOYA PROTOCOL (NP)**

## FIGURE 22: ACCESS AND BENEFIT SHARING (ABS) IN ACTION




knowledge so that the origins of this knowledge can be proven and illegal patents challenged (Traditional Knowledge Digital Library, India; http://www.tkdl.res.in/tkdl/langdefault/Common/home.asp?GL=Eng); and (iii) searches by journal publications or funders to check that resources that are the subject of papers have been legally accessed (used in Australia). (See Access and Benefit Sharing Clearing House (https://absch.cbd.int/) for links to ABS legislation.)

As the Protocol is so new, very few countries have had time to develop new access legislation. First impressions are that those that are primarily providers of biodiversity will be the first to start to redesign legislation. For example, Kenya, Ethiopia, Cameroon, South Africa, Peru, Ecuador, Costa Rica, Vietnam, South Korea, Malaysia and India are all at various stages of approving new legislation (E. C. Kamau, University of Bremen, pers. comm.). In most cases, countries will be introducing tight controls on access to their resources in an attempt to capture both monetary and non-monetary benefits that can be fed back into supporting vital conservation work and that can ensure equitable access for indigenous communities. There are, however, signs of a fundamentally different approach. Brazil has recently passed a new Biodiversity Law (Biodiversity Law No. 13, 123/15) that encourages free and open access to natural resources, and compliance measures to ensure that revenues from utilisation projects are received [211].

If Parties develop effective legislation to implement the Protocol, and put in place measures to monitor the utilisation of biodiversity to ensure compliance, there is the potential to offer a real incentive to conserve and sustainably use their natural resources [212].

## BOX 14. VALUE (IN US DOLLARS) OF GLOBAL MARKETS IN INDUSTRIES USING GENETIC RESOURCES:

### PHARMACEUTICALS

**$955.5 BN** (2011)

#### COSMETICS

**$426 BN** (2011)

#### BOTANICALS

**$84 BN** (2010)

Medicines and health and well-being products based on plant products

#### INDUSTRIAL BIOTECH

**$3.3 BN** (2010)

Industrial enzymes and microorganisms to create and improve new products, such as biofuels

### AGRICULTURE (crop protection, horticulture, breeding)

**$65–78 BN** (2010)

#### SEEDS

**$45 BN** (2011)

#### CROP PROTECTION

**$40 BN** (2010)

### FOOD AND BEVERAGES

**$11.6 TN** (2009)

#### FUNCTIONAL BEVERAGES

**$23.4 BN** (2010)

This growing market often follows new trends; for example, since the US Food and Drug Administration approved stevia as a sugar substitute, sales of this product have increased from $21 million in 2008 to $1–2 billion in 2014

SOURCE: LAIRD AND WYNBERG [206]

## BOX 15: TRADITIONAL KNOWLEDGE CASE STUDIES

### TURMERIC (*CURCUMA LONGA*):

In the mid-1990s, a patent was granted to a US university medical centre on the wound-healing properties of turmeric. These properties were well-known by Ayurvedic traditional healers in India [213], and the Indian Council of Scientific and Industrial Research (ICSIR) used 1,000-year-old Sanskrit writings to revoke the patent by proving that the use was neither a 'discovery' nor 'novel'. The patent also gave exclusive rights to sell and distribute turmeric, which raised grave concerns that current patent systems were unable to protect source countries and indigenous communities [214]. The revocation, on 13 August 1997 was the first such instance in the history of the US Patent and Trade Mark Office [215].

*Curcuma longa*

*Hoodia gordonii*

### *HOODIA GORDONII:*

A succulent endemic to South Africa, Botswana and Namibia, *Hoodia gordonii* has been used by the San people for generations to suppress hunger and thirst when on long bush walks in the Namib desert. The South African Council for Scientific and Industrial Research (CSIR) licensed the small UK-based company Phytopharm to develop and commercialise their patent on an extract of *Hoodia*. Following a critical media campaign, CSIR negotiated a retrospective benefit-sharing agreement with the San people, which gave them various social benefits and a promise of 6–8% of any commercial profits. In 2004, Phytopharm sub-licensed the Anglo-Dutch Company Unilever to develop *Hoodia* as a diet supplement [216, 217]. However, in 2008 Unilever dropped the development of *Hoodia*. The case illustrates the importance of having in place agreements with holders of traditional knowledge at the start of a project [218].

*Myristica fragrans*

## BOX 16: GENETIC RESOURCE CASE STUDIES

### NUTMEG (*MYRISTICA FRAGRANS*):

In July 2015, Colgate-Palmolive were granted patents in the EU for a nutmeg-based mouthwash and toothpaste. These were successfully challenged by the Indian Government, using sources digitised by the Traditional Knowledge Digital Library that documented nutmeg's use in dental hygiene in traditional medicine over thousands of years [219].

### *ARTEMISIA ANNUA:*

Thousands of small-scale farmers in Africa and Asia rely on selling *Artemisia annua* for the development of 'artemisinin', which is used in antimalarial drugs. Progress with biosynthesis suggests that in future the pharmaceutical industry could source artemisinin from a handful of microbial cell factories, potentially bypassing ABS requirements (Bill Gates project, 2014) and meaning provider countries and local people won't benefit.

*Artemisia annua*

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# Acknowledgements

The production of this report has been supported by numerous staff at Kew, our partner organisations and many individuals. In particular, we would like to thank the following (affiliated to RBG Kew unless otherwise stated):

David Baines, Dr Dan Bebber (University of Exeter), Emily Beech (BGCI), Oliver Bridle (Bodleian Libraries, University of Oxford), Julia Carretero, Helen Chadburn, Guy Clarke, Charlotte Couch, Alexandra Davey, Lauren Gardiner, Aurelie Grall, Pat Griggs, Craig Hilton-Taylor (IUCN), Dr Evanson Chege Kamau (University of Bremen), Isabel Larridon, Ben McCarthy (Plantlife International), Dr Gareth Richards (CAB International), Janet Scott (IUCN), Jacek Wajer (Natural History Museum), James Wearn, John Wiersema (USDA-ARS), and finally The Sylva Foundation (for hosting the web-based survey for the Steering Committee Delphi consultation). Support with the maps was provided by Justin Moat, Tim Wilkinson, David Benz (University of Oxford) and Numiko.

**Special thanks to the State of the World's Plant's strategic output group:** Steven Bachman, Marie Briggs, Martin Cheek, Colin Clubbe, Aaron Davis, Felix Forest, Serene Hargreaves, Marta Lejkowski, Justin Moat, Eimear Nic Lughadha, Matthew Smith (Microsoft) and China Williams

**We would like to thank those who reviewed drafts of the report:**
Professor Malcolm Press (Kew Science Trustee)
Professor Nicola Spence (Kew Science Trustee)
Professor Sue Hartley (Kew Science Trustee)
Dr Bridget Biggs (University of Oxford)
Professor John Birks (University of Bergen)
Professor Charles Godfray (University of Oxford)
Professor Steve Jackson (University of Arizona)
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**Design:** Jeff Eden

**Editorial support and copyediting:** Gina Fullerlove, Christina Harrison and Sharon Whitehead

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Photographs and images displayed in this document were kindly provided by the following people:

A. Dib, cover; W. Milliken, inside cover, 6, 31, 32 (top right, bottom left); I. Larridon, 4; J. Eden, 8, 46; C. Snak, 10, 12 (bottom right); F. Crawford, 12 (centre); J. van Veldhuizen, 12 (bottom left); P. Gonella, 12 (top right); S. Beckendorf, 12 (top left); W. Swanepoel, 12 (centre left); X. van der Burgt, 12 (centre bottom); S. Lancefield, 14, 17; Nazzu, 18; H. Rose, 22 (bottom right); L. Salazar/CWR Project, 22 (bottom left); P. Vilela, 22 (top left); P. Wilkin, 22 (right, top and second from top); P. Lewis/Department for International Development, 22 (right, second from bottom); rocharibeiro, 24; M. Cheek, 27 (top); G. Cooper, 27 (centre); Plantlife, 27 (bottom); F. Frazao, 28; F. Menegaz, 32 (top left); D. Zappi, 33 (bottom left), 75 (top); I. Ribeiro, 33 (top right); G. Damasceno, 33 (top left); N. Taylor, 33 (centre right); J. Edwards/Getty Images, 34; J. Carnemolla, 37; J. Williams, 38; Global Crop Diversity Trust, 39; J. Moat/Landsat imagery courtesy of NASA Goddard Space Flight Center and U.S. Geological Survey, 40; 24Novembers, 42; C. Clubbe, 49, 50; F. Suffert/Plant Pathology, 52; Y. Jin, 56; F. McQuaid/Plant Pathology, 57 (top); Royal Horticultural Society, 57 (bottom); F. Lanting, 58; L. Moraes/CNCFlora, 61; W. Sun, 62; CGP Grey, 64; Maky, 66; A. McRobb, 68, 74 (right); IISD/ENB, 70; J. Leong-Skornickova, 74 (left); C. Leon, 75 (bottom right).

**Citation**
This report should be cited as:
**RBG Kew (2016). The State of the World's Plants Report – 2016.**
**Royal Botanic Gardens, Kew**

**ISBN: 978-1-84246-628-5**

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

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