Royal Botanic Gardens
Kew

State of the World's Plants

2017

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Introduction to the State of the World's Plants 2017

A detailed knowledge of plants is fundamental to human life on Earth. Plants underpin all aspects of our everyday life – from the food that we eat, to the clothes that we wear, the materials we use, the air we breathe, the medicines we take and much more. These essential services provided by plants are far too often taken for granted. This is the second annual report in which we have scrutinised databases, published literature, policy documents, reports and satellite imagery to provide a synthesis of current knowledge on the world's plants.

Last year, our focus was predominantly on synthesising knowledge of the numbers of different categories of plants: How many vascular plants are currently known to science? How many are threatened with extinction? What is the number of plants with uses? etc. We also looked at the main threats to these plants, including climate change, land-use change, invasive plants, disease and over-exploitation. However, simply knowing how many plants there are and how many are under threat is not enough – what is also needed is an understanding of why some plants are more vulnerable than others. This year, therefore, we have also examined the emerging evidence for the characteristics of plants that appear to make some types less/more resilient to current and future threats.

It is not all doom and gloom, however. In this year's State of the World's Plants, we also highlight the rapidly accumulating discoveries and knowledge that provide important sign-posts to the next food crops, medicines, timbers etc. Information is now also emerging on the effectiveness of conservation actions and policies in protecting some of the most important plant species and communities across the globe. While there is still much more to do, these positive outcomes demonstrate that with scientific knowledge and evidence-based global actions, it is possible to conserve the extraordinary diversity of plants on Earth and to build on the unique combination of beauty and science which can together provide some of the solutions for the global challenges facing humanity today.

Professor Kathy J. Willis
Director of Science, RBG Kew

MAIN QUESTIONS ADDRESSED IN THIS REPORT

How many vascular plant families are there and how do we determine them?

What number of vascular plant species new to science were named in 2016?

Which plant species are being selected for whole genome sequencing, and why?

How many plant species are currently used as medicines?

How many Important Plant Areas (IPAs) are now recognised globally and how effective are they in protecting plant biodiversity?

What is the current status of knowledge on plants in Madagascar?

Which plant traits will enable species to tolerate current and future climate change?

How much of the Earth's terrestrial surface burns each year, which vegetation biome burns the most, and which plants are most flammable?

What are the most common methods used to control invasive plants, and which countries are carrying out the most research on their control?

Which pests pose the biggest threats to plants globally, and where is the greatest concentration of research effort on these pests?

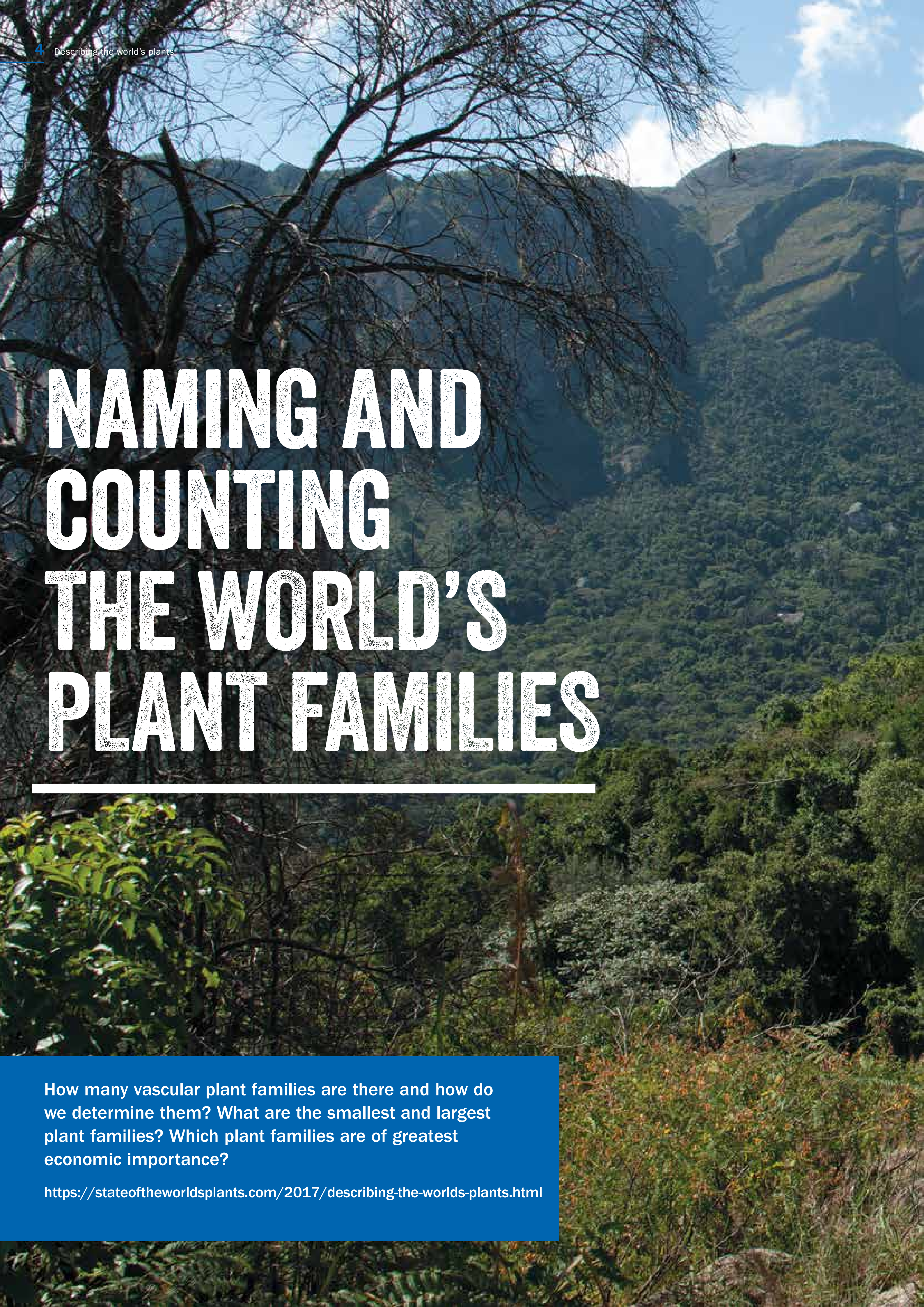
Are there particular biological attributes that make some plants more vulnerable to extinction threats than others?

What is the current status of international trade in endangered plant species, and how effective are current policies at policing international trade in wild plants?

EACH YEAR AROUND

340,000,000

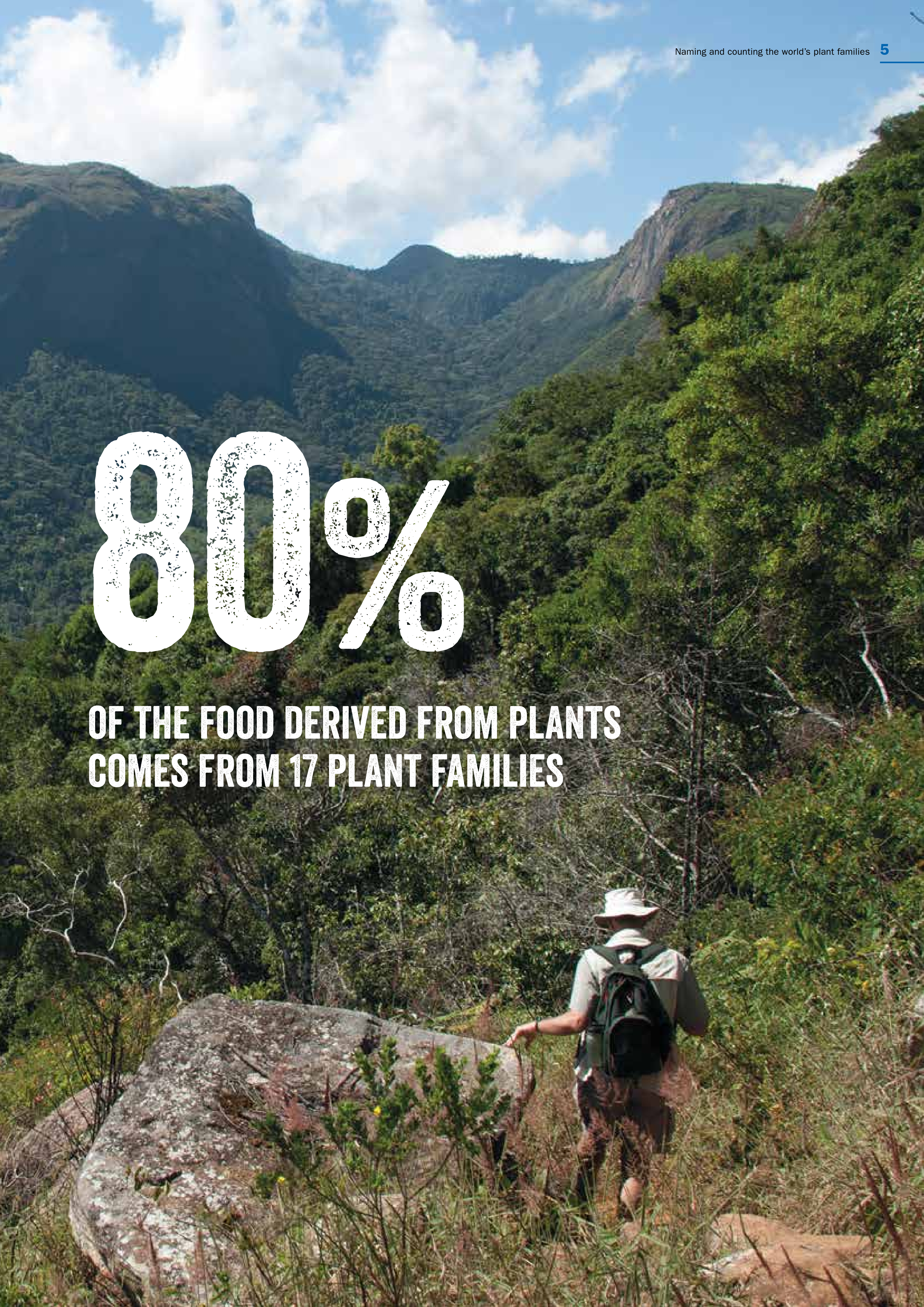
HECTARES OF THE EARTH'S VEGETATED SURFACE BURNS



NAMING AND COUNTING THE WORLD'S PLANT FAMILIES

How many vascular plant families are there and how do we determine them? What are the smallest and largest plant families? Which plant families are of greatest economic importance?

https://stateoftheworldsplants.com/2017/describing-the-worlds-plants.html



80%

OF THE FOOD DERIVED FROM PLANTS COMES FROM 17 PLANT FAMILIES

IN TOTAL, 452 VASCULAR PLANT FAMILIES HAVE BEEN IDENTIFIED BY BOTANISTS ACROSS THE WORLD.

The naming and counting of plants is an ongoing international effort. On average, around 2,000 new plant species are identified annually. Newly identified species are categorised according to their physical (morphological) and molecular characteristics, and their similarity to plants already known to science. This enables their evolutionary relatedness to other plants to be determined and thereby allows them to be placed in a plant family (Figure 1). In last year's *State of the World's Plants,* we reviewed the evidence for the number of vascular plant species currently known to science. This year, we turn our attention to plant families: to their number, the ways they have been determined over time, and our current knowledge of their distribution, diversity and uses.

Given the huge diversity of plants at species level, scientists have long sought to group plants into increasingly higher levels of organisation (e.g. genera, families and orders).

French botanist Antoine Laurent de Jussieu conducted some of the earliest attempts to group plants into families (see Box 1) and published his findings in *Genera Plantarum* in 1789. His approach was to group plants according to morphological characteristics that could be seen with the naked eye or a light microscope. Using similar approaches, George Bentham and Joseph Hooker, two Victorian botanists with a close association with Kew, recognised 197 families of flowering plants in their classification published in 1883[5]. A second major classification published 32 years later[6] recognised 303 plant families, and by 1981 this number had increased to 389[7] (see Figure 2). However, by then the limitations of using morphological characters alone to classify plants were starting to be realised – in part because some plants have few characters (e.g. some parasitic plants only have highly modified flowers and no leaves or stems), while others share superficially similar characters that may result in unrelated plants being classified together.

With the advent of DNA sequencing technologies in the 1980s and 1990s, scientists attempted to overcome some of the limitations of working strictly with morphology by exploring the potential of using molecular information to shed light on evolutionary relationships between plants. This led to the establishment of an international collaboration between scientists to explore the evolutionary relatedness of flowering plants (angiosperms) called the Angiosperm Phylogeny Group (APG). They published the first classification of flowering plants underpinned by molecular data in 1998[8]. This revised classification recognised 462 families of flowering plants and provided the first molecular insights into how these different families were related.

Although many of the relationships between plant families based on morphological data were confirmed with the DNA analyses, there were also some surprising and unexpected findings. For example, the water lilies (*Nymphaea*) and the Indian lotus (*Nelumbo*) had traditionally been considered to be closely related based on their broadly similar morphologies and aquatic habitats. However, the APG classification showed that these two genera actually belonged to two distantly related families in completely different orders. Thus, while *Nymphaea* was placed in Nymphaeaceae (order Nymphaeales) and considered to be one of the earliest diverging lineages of flowering plants, *Nelumbo* was placed in Nelumbonaceae in the order Proteales and hence was more closely related to the plane tree (*Platanus*) and relatives than the true water lilies (see Box 2).

Since 1998, as DNA sequencing techniques have become cheaper and easier, further revisions of the APG classification have been undertaken. The latest revision, APG IV published in 2016[9], recognised 416 families of flowering plants. The use of molecular data has also led to similar progress in our understanding of the evolutionary relationships in other groups of vascular plants. For example, the latest classification of ferns, horsetails and lycopods (clubmosses and quillworts), produced in 2014, revealed an estimated 11,835 species in 24 families[10], and work on gymnosperms (including conifers, cycads and ginkgo) recognised 1,113 species in 12 families[1]. The obvious disparities in numbers of families recognised versus the number of species in a group (e.g. gymnosperms versus angiosperms) are the result of large numbers of extinctions in some lineages. For example, the fossil history of gymnosperms includes an enormous diversity; the modern groups are merely sparse remnants of what existed previously and thus by chance include only a few families.

FIGURE 2: A TIMELINE SHOWING THE HISTORY OF CLASSIFYING FLOWERING PLANTS INTO FAMILIES[5–9],[11–12]

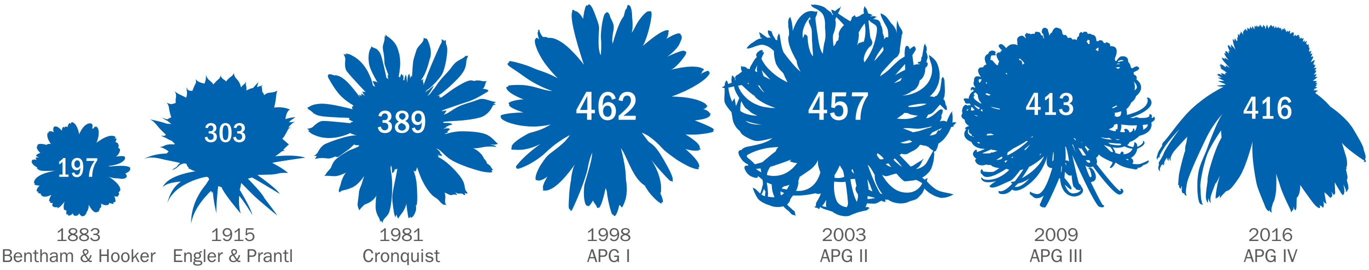
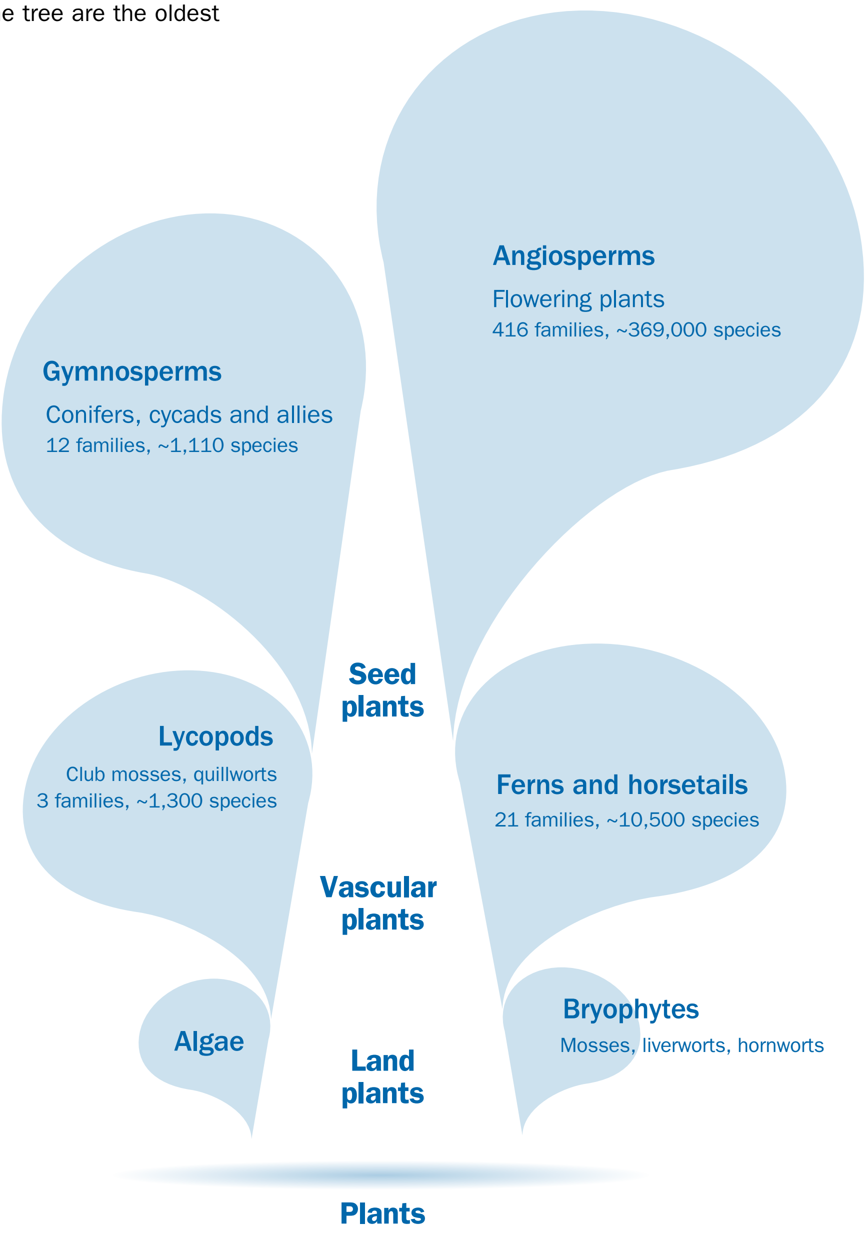


FIGURE 1: SIMPLIFIED DIAGRAM TO ILLUSTRATE THE RELATIONSHIPS BETWEEN THE MAJOR GROUPS OF PLANT FAMILIES AND SPECIES NUMBERS[1–4,10]

Groups at the bottom of the tree are the oldest in evolutionary terms.



BOX 1: WHAT MAKES A PLANT FAMILY?

The definition of what constitutes a family differs between major groups of organisms (e.g. birds versus plants) and, in most, what is recognised as a family has a great deal to do with tradition. With plants, you can see in the writings of the Ancient Greeks, such as Theophrastus, that they recognised the existence of sets of plants with a common design (e.g. orchids, legumes, daisies). Family is thus a rank of classification that associates genera that share some set of what are considered to be the more important or significant features. In some cases, families have needed to be redefined when it has been found through morphological and/or molecular (DNA) studies that one family is embedded in another (in such circumstances they are merged), but many plant families have a long history of recognition.

When it has been found that a genus or group of genera does not share the genetic make-up of the family in which they have been classified, the question considered is whether they fit better in another, already recognised family or whether they should be placed in their own, newly described family. Through this process of evaluating genetic relatedness, we have come to the set of plant families recognised today. It is this process that has resulted in the changing numbers of families recognised, as DNA technology has improved and newly discovered results have enhanced our understanding of plant evolution.

THE LARGEST AND SMALLEST VASCULAR PLANT FAMILIES

Twenty flowering plant families each have more than 3,000 species, covering approximately 46% of all vascular plants[1,10]. The largest family is Asteraceae with over 32,500 species. Asteraceae, sometimes called Compositae, is widespread and commonly known as the daisy family (see Box 3).

The five largest families of flowering plants are as follows:

FAMILY	**NUMBER OF SPECIES**
Asteraceae (daisies)	32,581
Orchidaceae (orchids)	28,237
Fabaceae (legumes)	20,856
Rubiaceae (coffees and bedstraws)	13,686
Poaceae (grasses)	11,434

SPECIES 2000 & ITIS CATALOGUE OF LIFE – www.catalogueoflife.org/col; WORLD CHECKLIST OF SELECTED PLANT FAMILIES, ROYAL BOTANIC GARDENS, KEW – http://apps.kew.org/wcsp/

The smallest families have only one species (monotypic). There are 33 of these, which equates to just under 8% of all vascular plant families but less than 0.01% of all species. Sixteen monotypic families are endemic to one country, with six in Australia, three in South America and two in Africa. Others are more widespread – the most widespread monotypic family being Scheuchzeriaceae (*Scheuchzeria palustris*, commonly known as rannoch rush), which has a North Temperate distribution covering over 40 countries, including the UK where it grows on Rannoch Moor.

The largest families of gymnosperms are Zamiaceae (a group of cycads containing 232 species) and Pinaceae (pines, containing 231 species). There are three monotypic gymnosperm families: Sciadopityaceae (Japanese umbrella-pine), which is endemic to Japan; Welwitschiaceae (welwitschia), which has a distribution from south-west Angola to western central Namibia; and Ginkgoaceae (ginkgo), which is endemic to southern China.

The largest family of ferns is Polypodiaceae (polypod ferns) with 4,080 species, and there is a single monotypic family. The largest lycopod family is Selaginellaceae with 700 species.

FAMILIES OF ECONOMIC IMPORTANCE

Eighty per cent of the food derived from plants comes from 17 plant families[13]. The most important of these are Poaceae, Fabaceae (see Box 4) and Brassicaceae (cabbages). A recent inventory[14] that incorporates minor crops and crop wild relatives (which are important for food security and future breeding and development), includes 37 families, comprising those mentioned before but also Rosaceae, due to 150 species of *Prunus* (cherries, almonds, peaches, apricots and plums). The top families for use in medicine are somewhat different, although legumes are still an important family on this list. In terms of plant families that contain economically important timber, there are 1,575 species distributed across 103 families, with by far the largest being Fabaceae, followed by Dipterocarpaceae (dipterocarps; 118 species) and Pinaceae (pines; 74 species). These top three families account for 31% of all timbers used[15].

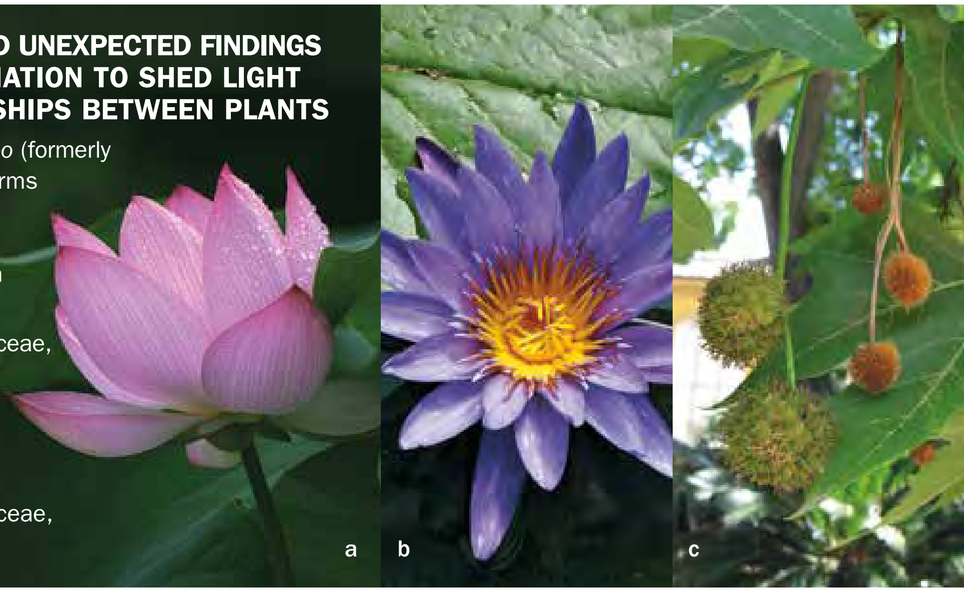
BOX 2: ONE OF THE SURPRISING AND UNEXPECTED FINDINGS FROM USING MOLECULAR INFORMATION TO SHED LIGHT ON THE EVOLUTIONARY RELATIONSHIPS BETWEEN PLANTS

Results from molecular data revealed *Nelumbo* (formerly grouped with the water lilies) is closest in terms of its evolutionary relationships to the family Nelumbonaceae. It is therefore more closely related to the family containing species such as plane trees, than to true water lilies.

a *Nelumbo nucifera,* of the family Nelumbonaceae, commonly known as the sacred water lotus

b *Nymphaea nouchali* var. *caerulea* of the family Nymphaeaceae, commonly known as the water lilies

c *Platanus* x *hispanica*, of the family Platanaceae, commonly known as the London plane

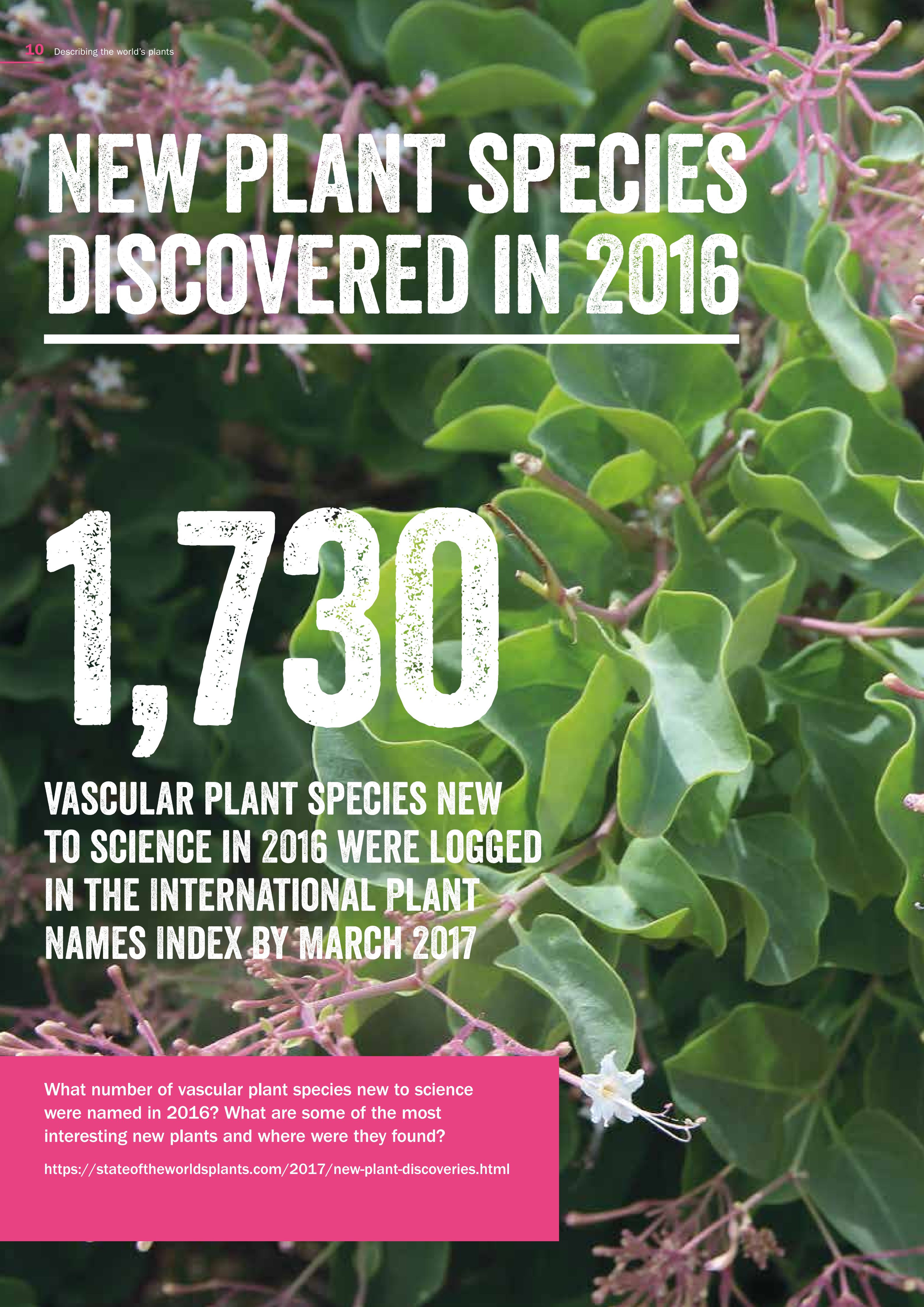


BOX 3: ASTERACEAE (DAISIES)

Asteraceae, also known as the Compositae, is the largest family of flowering plants. The family has a worldwide distribution and is found from sea level to the highest mountains. The most obvious and characteristic feature of Asteraceae is that the florets (small flowers) are grouped into compact heads (capitula or pseudanthia) that often superficially resemble individual flowers (e.g. sunflower or daisy). Additionally, they usually disperse their progeny in single-seeded fruits (achenes or cypselas), sometimes with a distinctive modified calyx called a pappus (e.g. in the dandelion). The family includes weeds, such as ragwort (*Senecio jacobaea*) and thistles (e.g. *Cirsium*). However, it also produces many economically important and useful products: for example, sunflower oil from *Helianthus annuus*; herbal teas, such as chamomile from *Matricaria chamomilla*; vegetables including globe and Jerusalem artichokes (*Cynara cardunculus* and *Helianthus tuberosus*); and horticulturally important plants, such as marigolds (*Calendula* and *Tagetes*), *Chrysanthemum* and *Dahlia*.

BOX 4: FABACEAE (LEGUMES)

Fabaceae (or Leguminosae) has a cosmopolitan distribution. In early 2017, the legume systematics community published a new six-subfamily classification[16]. Although commonly known as the pea and bean family, legumes are far more diverse in growth form, ranging from herbs and shrubs to large woody lianas and huge canopy-emergent trees; a few are floating aquatics. The family takes its name from its most common fruit type – a legume, or pod. Legumes are widely used as human and animal food, for timber, in dyes, insecticides and medicinal products, and as garden, park and street ornamentals. A subset of legumes are known as pulses; these include dried peas and beans, lentils and chickpeas. Peanuts (*Arachis hypogaea*) and soya (*Glycine max*) are also economically important legume crops. Many legumes have nodules on their roots that house nitrogen-fixing bacteria. This ability to fix atmospheric nitrogen provides an additional source of fertiliser for the plant and allows their cultivation in relatively poor soils. Nitrogen-fixing legumes, including alfafa (*Medicago sativa*) and clover (*Trifolium incarnatum* and *T. pratense*), can also be used as 'green manures' in crop rotation systems.



NEW PLANT SPECIES DISCOVERED IN 2016

1,730

VASCULAR PLANT SPECIES NEW TO SCIENCE IN 2016 WERE LOGGED IN THE INTERNATIONAL PLANT NAMES INDEX BY MARCH 2017

What number of vascular plant species new to science were named in 2016? What are some of the most interesting new plants and where were they found?

https://stateoftheworldsplants.com/2017/new-plant-discoveries.html

Englerophytum paludosum

Englerophytum paludosum

>>

A new, Endangered,

39 METRES TALL

forest tree, with a trunk over a metre wide, from Korup, Cameroon

Tessmannia korupensis

Tibouchina rosanae

Crossopetalum mossambicense

>>

A new, Vulnerable species of "African *Bougainvillea*" from gypsum rocks in Ethiopia, is the largest known, reaching

3 METRES TALL

Manihot tombadorensis

Commicarpus macrothamnus

NEW PLANT SPECIES DISCOVERED AND DESCRIBED IN 2016 INCLUDE THOSE OF INTEREST FOR HORTICULTURE, PLANTS OF ECONOMIC IMPORTANCE (FOOD, FODDER, MEDICINAL PLANTS, TIMBER, AND HERBS AND SPICES) AND COUNTRY-BASED NOVELTIES.

The process of cataloguing new plant discoveries is normally via publications in taxonomic journals. The main audience for these outlets is specialist: principally other taxonomists.

Occasionally, new plant discoveries are disseminated to a wider audience via other media outlets such as newspapers and social media. In last year's *State of the World's Plants,* we published a list of new plant species discovered in 2015, to make these records more widely available. We were overwhelmed by the global interest in this information. Facts that were of particular interest included that c.2,000 new plant species are still being discovered each year, and that new plants included 105-tonne trees, important new crop wild relatives, and 1.5 m tall carnivorous plants. This year, therefore, we have repeated the exercise.

NEW SPECIES OF HORTICULTURAL INTEREST

For the temperate climate areas of the world, there have been multiple discoveries made in both China and Turkey. Those from China include species of *Rosa* (roses), *Clematis, Aconitum, Impatiens* (busy-lizzies), *Primula, Rubus, Thalictrum, Ligularia, Delphinium, Epimedium, Senecio, Spiraea, Sorbus* and *Ulmus*. From Turkey, new species of *Viola* (violets), *Dianthus* (pinks and carnations), *Gypsophila, Silene* (campions), *Achillea* (millefoils) and *Centaurea* (knapweeds) were found. In addition, two new *Camellia* species were found in Vietnam[1,2], and a new *Meconopsis* in Bhutan. A new *Matthiola* (stock) was discovered in Iran, and nine new *Lobelia* were discovered, mostly from Mexico. Two *Gerbera* were discovered in South Africa[3], a new oak (*Quercus meavei*) in Mexico[4], and a new alpine gentian (*Gentiana woodii*) in Bolivia[5].

A number of new species of horticultural interest have also been discovered in the tropical forests of South America and South-East Asia. These include a large number of species of orchids (336), and 11 new species of *Aspidistra*, mainly from forests in Vietnam. Twenty-nine new species of *Begonia* have been discovered, mainly from forests of Malaysia, while, mainly from Colombia, 10 new species of *Passiflora* were found. In addition, two new *Nepenthes*, (carnivorous pitcher plants), from Sulawesi in Indonesia were published[6,7]. Sixty-six new aroids were published, mainly *Philodendron* from Ecuador (30 species) but also species of *Amorphophallus, Anthurium*, *Arisaema* and the aquarium-cultivated genus *Cryptocoryne*, from Borneo and Sumatra[8].

From the drier environments of Central and South America, 12 new species of cacti were published, including new species of *Rebutia, Echinopsis, Rhipsalis* and *Gymnocalycium*.

NEW SPECIES OF ECONOMIC IMPORTANCE

1. Food and drink. Among the most important discovered species with potential for new food sources were 11 new Brazilian species of *Manihot*, representing a 10% increase in the known number of species that are relatives of the important food plant *Manihot esculenta*[9]. This plant is known variously as cassava, garri, manioc or tapioca and is a staple food for millions of people in the tropics, where Nigeria is the largest producer. Third in global importance after maize and rice, manioc offers more food security than cereals because tubers can be left in the ground until needed, can be harvested at any season and contain sufficient cyanide to deter crop pests.

Seven new species of *Aspalathus* have also been discovered – the South African genus best known for redbush, or rooibos, tea. Unfortunately, six of these seven new species are already threatened with extinction, with one being Critically Endangered, two Endangered and three Vulnerable[10].

Other discoveries of plants with close affinities to current species used as crops, fruit and food flavouring, include a new species of yam in the genus *Dioscorea* found in Brazil[11]. A new parsnip, *Pastinaca*, was discovered from Turkey[12]; a new caper, *Capparis*, from the Philippines[13]; a ginger, *Zingiber*, from the Far East; *Durio*, from Borneo[14]; *Vanilla*, from Brazil[15]; and *Angelica* from Turkey[16]. There have also been important advances in our knowledge of sugar cane, *Saccharum*, which currently provides more than half the world's sugar. It has long been thought that the world's sugar cane cultivars evolved in New Guinea from a complex aggregate of hybrids named as *S. officinarum*. New research analysing the chloroplast genomes of *Saccharum* has shown that these crop cultivars evolved in Polynesia from a species newly named in 2016 as *Saccharum cultum*[17].

2. Fodder crops. Further important discoveries in 2016 included plant species for use in fodder crops. Sainfoins (*Onobrychis*), have long been used as fodder plants, to increase the protein uptake in ruminants. They are also of interest because of their phytochemical composition, since the condensed tannins they contain reduce greenhouse emissions from ruminants. So the discovery of *Onobrychis citrina*, from limestone mountains in Greece[18], may have benefits for animal husbandry.

3. Medicinal plants. Species of the genus *Mucuna* are cultivated to provide a treatment for Parkinson's disease. They contain L-DOPA, a dopamine precursor. Nine new species of this climbing vine genus, which is an irritant and therefore a health and safety hazard for fieldworkers prospecting in the tropics, were published in 2016: seven from the Old World (South-East Asia: Borneo, New Guinea, and Luzon)[19], and two from the New World (Ecuador and Mexico)[20]. Four new relatives of *Aloe vera*, widely used in the cosmetics and pharmaceutical industries, were published from southern Africa.

4. Timber. Arguably the most high-profile new genus published in 2016 is *Paubrasilia*, which includes the species hitherto known as *Caesalpinia echinata* or 'pau brasil'[21]. Brazil was named after this now endangered legume tree,

Begonia rubrobracteolata

TWENTY-NINE NEW SPECIES OF *BEGONIA* HAVE BEEN DISCOVERED, MAINLY FROM FORESTS OF MALAYSIA

and its wood is still of high value, particularly prized for the production of violin bows. Five new species were recognised from Gabon[22] .

Also from Gabon came the discovery of five new species of rosewood – genus *Dalbergia*[22] . All species of this genus were listed on CITES in 2016 due to illegal over-exploitation of some species for timber, particularly in Madagascar and primarily to supply woods for the musical instrument industry.

5. Herbs & Spices. Six new species of *Salvia* – the genus commonly known and used as the herb sage but which also contains species with horticultural and hallucinogenic uses – were described from China, Iran and Mexico. The large genus *Syzygium* (Myrtaceae), best known for cloves (*Syzygium aromaticum*; native to the Moluccas in Indonesia), gained 12 new species in 2016, including six from Sumatra and three from the Comoros Islands east of Africa[23].

NEW COUNTRY-BASED NOVELTIES

From tropical South America, 30 more new species from the clove family Myrtaceae have been discovered, mainly from the last remnants of the species-diverse Brazilian Atlantic Forest, along with 27 new species of rainforest trees in the genus *Sloanea* (Elaeocarpaceae), mainly from the Andes and Central America[24]. Ten new tree species of *Trichilia* in the mahogany family (Meliaceae) also came to light. Eleven new neotropical species were also added to the genus *Psychotria*, mostly from the western Amazon Basin and Andes. *Psychotria* is the largest genus of the coffee family (Rubiaceae). These are usually shrubs and small trees of rainforest understorey. Four new morning-glories (*Ipomoea*; Convolvulaceae) and three *Mimosa* species (Fabaceae) were published from Paraguay, Brazil and Bolivia, and also from Bolivia a new *Oxypetalum* (Apocynaceae).

From tropical Asia, new discoveries include a new *Areca* palm (Arecaceae) from New Guinea, two new *Rafflesia* (Rafflesiaceae) from Borneo and the Philippines, three new *Artabotrys* and *Polyalthia* (Annonaceae) from Malaysia, a new *Lysimachia* (Primulaceae) from Thailand, a new *Eranthemum* (Acanthaceae) from Myanmar, two new *Scutellaria* (Lamiaceae) from Burma and Thailand, and a new *Elaeocarpus* (Elaeocarpaceae) tree from Borneo. In the grass family (Poaceae), two new genera of bamboo, *Ruhooglandia* and *Widjajachloa,* were published from New Guinea[25], another, *Yersinochloa*, from Vietnam, and a fourth, *Kuruna*, from Sri Lanka and southern India[26]. New species of bamboo were also published in the genera *Dendrocalamus* from China and *Schizostachyum* from Malaysia and Vietnam.

From continental Africa, a new genus of shrub, *Karima* (Euphorbiaceae)[27], was discovered as a result of an environmental impact assessment for a planned hydroelectric dam near river rapids in Sierra Leone. New *Inversodicraea* and *Macropodiella* (Podostemaceae) from river rapids in Guinea and Ivory Coast were also published. New forest species of spiny tree *Allophylus* (Sapindaceae) were published from remnants of lowland rainforest in Guinea-Liberia and Cameroon[28], and a new climbing *Psychotria* (Rubiaceae) from patches of cloud forests of the Guinea Highlands. Africa's first endemic *Calophyllum* (Calophyllaceae) was found during an impact assessment for a uranium mine in southern Mali. With fewer than ten mature trees known, it is Critically Endangered.

From Cameroon, two new grove-forming leguminous canopy trees, *Didelotia* and *Tessmannia* were published from the Korup Forest[29], together with *Gambeya korupensis* (Sapotaceae). Also from West Central Africa were four new species of *Englerophytum,* while a new hemi-epiphytic aroid, a *Rhaphidophora*, was published from the Bakossi Forest in Cameroon[30].

Perhaps the most amazing and unexpected new species was from the species-diverse family Acanthaceae, usually herbs and low shrubs. However, the newly discovered Tanzanian *Barleria mirabilis* is a tree[31]! Also from Tanzania were a new *Tephrosia* (Fabaceae) and a new *Conyza* (Compositae)[32]. From gypsum outcrops in eastern Ethiopia came two new shrubby *Commicarpus* (Nyctaginaeae)[33]. A new milkwort (*Polygala*; Polygalaceae) was reported from Zambia[34], and four new *Cissus* (Vitaceae) were discovered from fossil seeds near Lake Victoria[35].

Madagascar saw a great harvest of new species for 2016. Surely the most wonderful was the new genus *Sokinochloa* (Poaceae)[36]. These, so far seven, species of climbing, forest bamboos, have spiky, ball-like flower clusters; sokina is Malagasy for hedgehog. Since these bamboos only produce flowers at intervals of around ten (sometimes as much 50 or more) years, much patience was needed to await their appearance in order to identify and describe the species.

Other new species from Madagascar include *Seychellaria barbata* (Triuridaceae), a forest shade plant without chlorophyll that derives its nutrients from fungi[37], a flamboyant new *Podorungia* (Acanthaceae)[38] and two new *Canephora* (Rubiaceae)[39].

Finally, the largest single block of new plant taxa for 2016 was published posthumously by Alan Radcliffe-Smith, whose last years of retirement were spent revising the species-rich genus *Croton* (Euphorbiaceae) for Madagascar. He described 150 new species, subspecies and varieties[40]. Members of this genus of trees and shrubs are well known and appreciated in Madagascar for their medicinal properties. Crotons have three different classes of biochemical compounds with medical applications: diterpenoids, active alkaloids and essential oils.

PLANT GENOMES – PROGRESS AND PROSPECTS

What plant species are being selected for whole genome sequencing and why? How is the new knowledge generated from these whole genome sequences being used in both fundamental and applied biological questions?

https://stateoftheworldsplants.com/2017/plant-genomics.html

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PLANT SPECIES NOW HAVE WHOLE GENOME SEQUENCES – AND RISING

> THE SEQUENCE OF DNA IN PLANTS IS A REPOSITORY OF HUGE AMOUNTS OF USEFUL INFORMATION THAT CAN BE PUT TO A GREAT VARIETY OF USES, FROM ELUCIDATING THE EVOLUTIONARY RELATIONSHIPS BETWEEN DIFFERENT PLANT SPECIES TO DETERMINING THE ORIGIN OF TROPICAL TIMBER.

This year has seen huge and exciting advances in both the amounts and types of genomic data that have been generated, as well as the computational approaches needed to interpret them[e.g.1–4]. In the medical field, such advances are, for example, now starting to make personalised medicine a reality[5]. For agriculture and biodiversity, a wealth of new data promises new ways to increase food security, alleviate poverty, inform species conservation programmes and improve ecosystem services[6–10]. In addition, these advances are stimulating ever more ambitious projects in the study of evolutionary relationships across the plant tree of life[e.g.11–14].

As DNA sequencing costs continue to plummet, the number of plant species with assembled draft whole genome sequences available online is rising. Even since the first *State of the World's Plants* report in May 2016, the number has risen from 139 to 225 (in January 2017) – an increase of 62% in just 7 months (Figure 1). So what plant species are being selected for sequencing and why?

Most species with whole genome sequences are crops (Figure 2), with food crops comprising the biggest fraction. They not only include the three major cereals, that together contribute > 50% of the globally consumed calories[15] (i.e. rice[16,17], maize[18], and wheat[19,20]), but also an increasing diversity of other species grown for food. Fruits and vegetables such as pineapples (*Ananas comosus*[21]), strawberries (*Fragaria* x *ananassa*[22]) and carrots (*Daucus carota* subsp. *carota*[23]) have been sequenced. So have plants that provide the raw ingredients for our favourite beverages such as coffee (*Coffea robusta*[24]), wine (grapes, *Vitis vinifera*[25]) and beer (hops, *Humulus lupulus*[26]), and comfort food such as chocolate (*Theobroma cacao*[27]). Not only are these studies identifying key genes involved in enhancing yield but they are also shedding light on the pathways which contribute to taste and food quality. For example, the sequencing of the hop genome has uncovered how the metabolic pathways impacting taste and flavour in beer are regulated[26], while analysis of the hot pepper genome (*Capsicum annuum*) has shed new light on the biochemical pathways synthesising the capsaicinoid alkaloids that generate the sensation of heat and have nutritional value and health benefits[28].

FIGURE 1: CUMULATIVE NUMBER OF SPECIES WITH WHOLE GENOME SEQUENCES (2000–16)

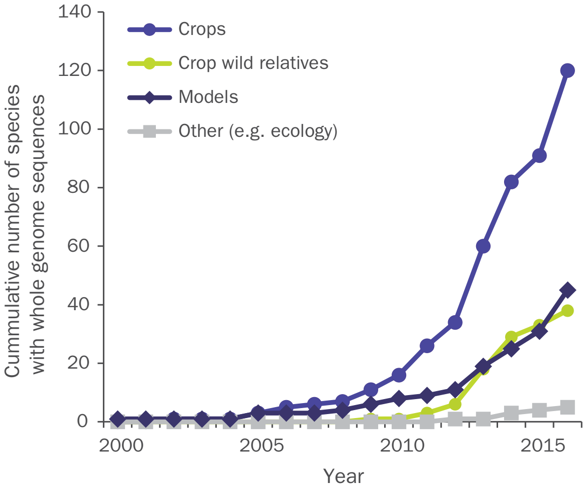
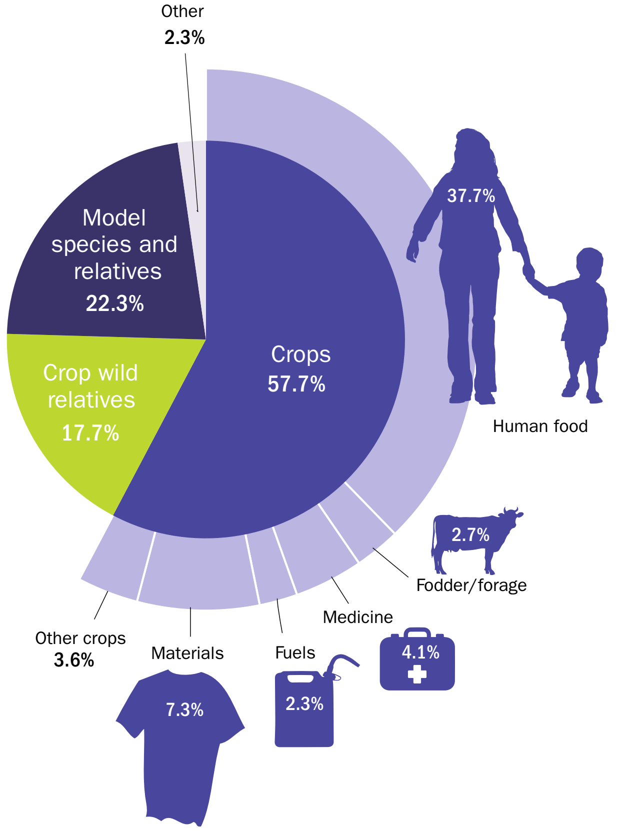
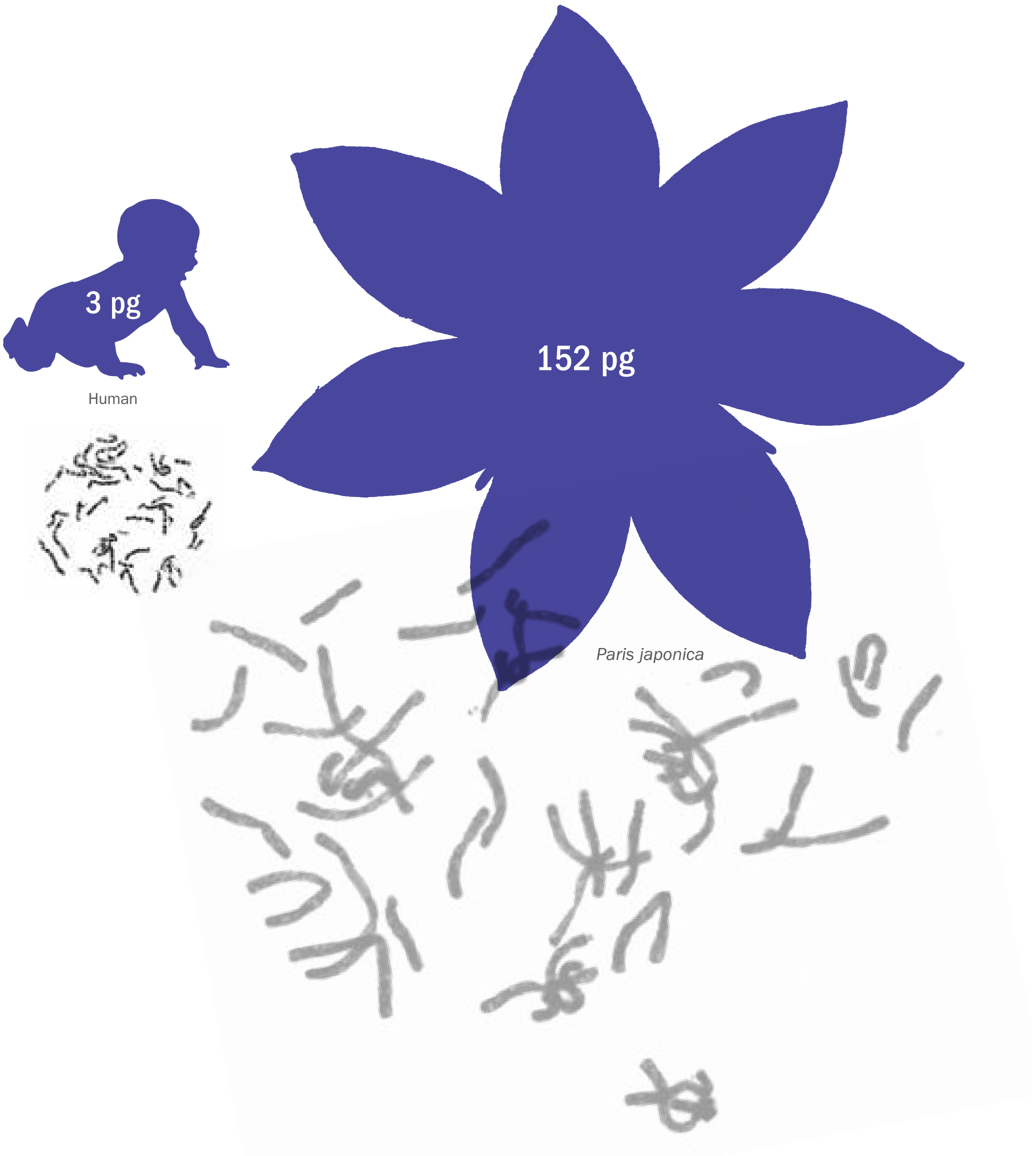


FIGURE 2: CURRENT USAGE OF PLANTS WHOSE WHOLE GENOMES HAVE BEEN SEQUENCED



Other food crops that have started to receive attention include orphan and under-utilised crops such as buckwheat (*Fagopyrum esculentum*)[29], the 'tree against hunger' (*Ensete ventricosum*)[30] and most recently quinoa (*Chenopodium quinoa*)[31], which is often referred to as the 'king of the grains' due to its highly nutritious seeds (rich in essential amino acids, dietary fibre, minerals and vitamins). Such crops are important to many of the poorest people on Earth and yet,

FIGURE 3: THE GENOME OF THE PLANT *PARIS JAPONICA* HAS 50X MORE DNA THAN THE HUMAN GENOME – THIS IS REFLECTED IN THE SIZES OF THE CHROMOSOMES, WHICH ARE SHOWN HERE AT THE SAME MAGNIFICATION (1 pg = 10^{-12} g)



to date, have received little attention from scientists compared with more widely grown crops. Having whole genome sequences from such species will provide a substantial boost towards understanding their key traits, enabling targeted breeding programmes and application of the latest advances in crop improvement, such as genomic selection[6] and, potentially, CRISPR/Cas9 gene editing approaches[32].

Beyond food, the sequencing of crops with a diversity of other uses (e.g. medicines, natural products, biofuels and materials such as timber) is starting to increase. For example, sequencing medicinal plants offers the potential to identify and generate exciting and novel data on the biochemical pathways involved in synthesising the bioactive compounds. Chinese liquorice (*Glycyrrhiza uralensis*)[33] is one of the most widely used traditional herbal medicines, with a history of use dating back 2,000 years, due to its wide range of pharmacological properties (e.g. anti-inflammatory, anticancer and antiviral activities[34]). Its whole genome sequence was announced in January 2017[34], and it is hoped that the new detailed insights into genes coding for some of the medicinally important compounds such as glycyrrhizin will open up opportunities for bioengineering production of these compounds on a large scale, using synthetic biology and targeted breeding approaches. In a similar way, the recent release of the Madagascan periwinkle (*Catharanthus roseus*) genome sequence[35], the key source of the widely used anticancer drugs vinblastine and vincristine, will enable the complex specialised metabolic pathways of their synthesis to be more fully understood and utilised.

While much is being learnt from the study of crop genomes, studying the genomes of crop wild relatives (CWR) is also important. These plants, which are defined as 'a wild plant taxon that has an indirect use derived from its relatively close genetic relationship to a crop'[36], can provide essential insights[37,38]. This is because CWR genomes harbour important genetic diversity (often lost during crop domestication) that can be used for breeding resilience into crops[37]. An increasing number of CWR species are now being sequenced, with recent additions including two of the CWRs of the cultivated peanut (*Arachis hypogaea*) – an important nutritious food source for many farmers in the developing world (annual production of c.46 million tons)[39]. The whole genome sequences will provide breeders with new tools for enhancing the crop, and for developing new drought, insect and disease resistant varieties.

There is growing realisation that whole genome sequencing of some of the dominant species in ecosystems is also needed, to enhance understanding of ecological

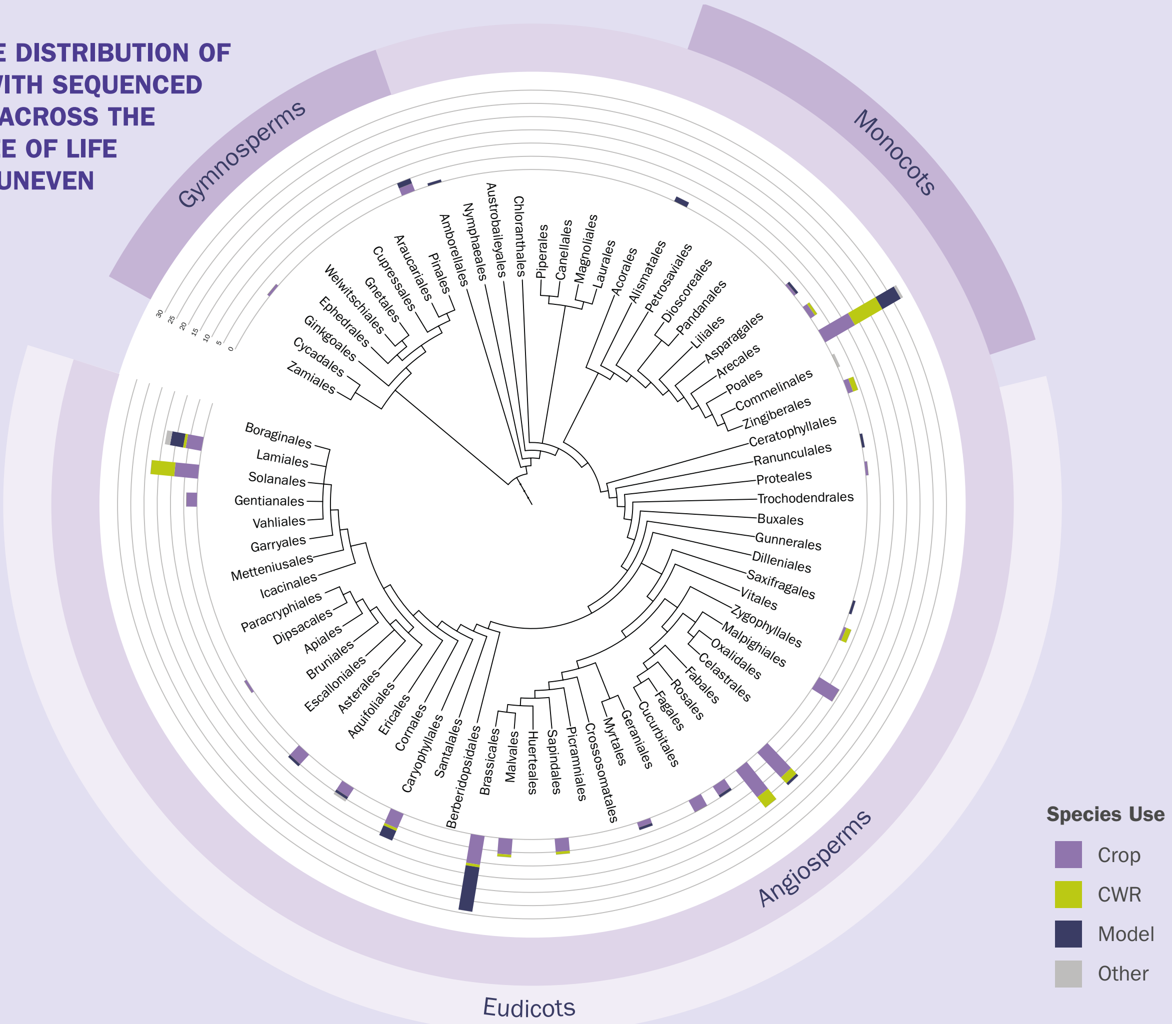
processes, and conserve biodiversity and ecosystem services (Box 1). A recent significant example is the sequencing of the ash tree (*Fraxinus excelsior*) genome[40] – a species that is under threat from a fungus causing ash dieback across northern Europe. Whole genome sequencing, together with other molecular data, promises the identification of resistant individuals that can be planted before the existing stands have succumbed to the disease, mitigating against damage to European countryside ecology.

The final reason for selecting species for whole genome sequencing is because they serve as model plants to enhance our understanding of fundamental biological, ecological and evolutionary processes. While some species are selected for specific reasons (e.g. *Oropetium thomaeum* and *Eutrema salsugineum* were sequenced to understand desiccation and salt tolerance, respectively[41,42]), others are selected because of their pivotal evolutionary position (e.g. *Amborella trichopoda* was sequenced to provide insights into the ancestral angiosperm genome[43]). The most widely studied model, and indeed the first species to have its whole genome sequenced, in 2000, is *Arabidopsis thaliana*[44] in the cabbage family (Brassicaceae). The insights gained from this genome assembly, together with ongoing studies, have established much of what is known about the molecular mechanisms underpinning plant physiology and development. It remains one of the most intensely studied plant genomes. For example, the recent release of whole genome sequences for 1,135 accessions of *A. thaliana* is providing new understanding on how variation at the molecular level translates into the phenotypic variation observed in nature[45]. Whole genome sequencing has also been extended to a wide range of related species, including some grown as crops (e.g. oilseed rape, *Brassica napus*[46], and Chinese cabbage, a subspecies of *Brassica rapa*[47]) to provide insights into the evolutionary dynamics of this diverse and economically valuable plant family[48,49].

The advances in sequencing and bioinformatic technologies (see Box 2) are underpinned by knowledge of the plant's genome size (i.e. the amount of DNA in the nucleus), as this information is essential for assessing the amount of DNA needed to sequence (with significant financial and time cost implications) and the quality and completeness of the assembled genome. Until now, the majority of species sequenced have genome sizes that are not so different from our own which is c.3 pg (1 pg = 10^{-12} g), and they fall at the lower end of the c.2,400-fold range of genome sizes encountered in plants (0.063–152 pg)[50]. Yet many species have considerably larger genomes, with the largest so far recorded in a monocot (*Paris japonica*[51]) and a fern (*Tmesipteris obliqua*[52]), each containing c.50x more DNA than our own genome (Figure 3). Such information is invaluable, as genome size is a plant trait that can influence many aspects of a plant's development, ecology and evolution.

Overall, these whole genome sequencing studies, combined with genomic data generated from a diversity of other approaches, are enabling deeper understanding of plant evolution and diversity and providing insights into fundamental ecological processes and agriculture. These insights are essential if we are to respond appropriately to a growing human population and increase standards of living, while maintaining biodiversity and effective ecosystem services in the face of anthropogenic and climate-induced environmental changes.

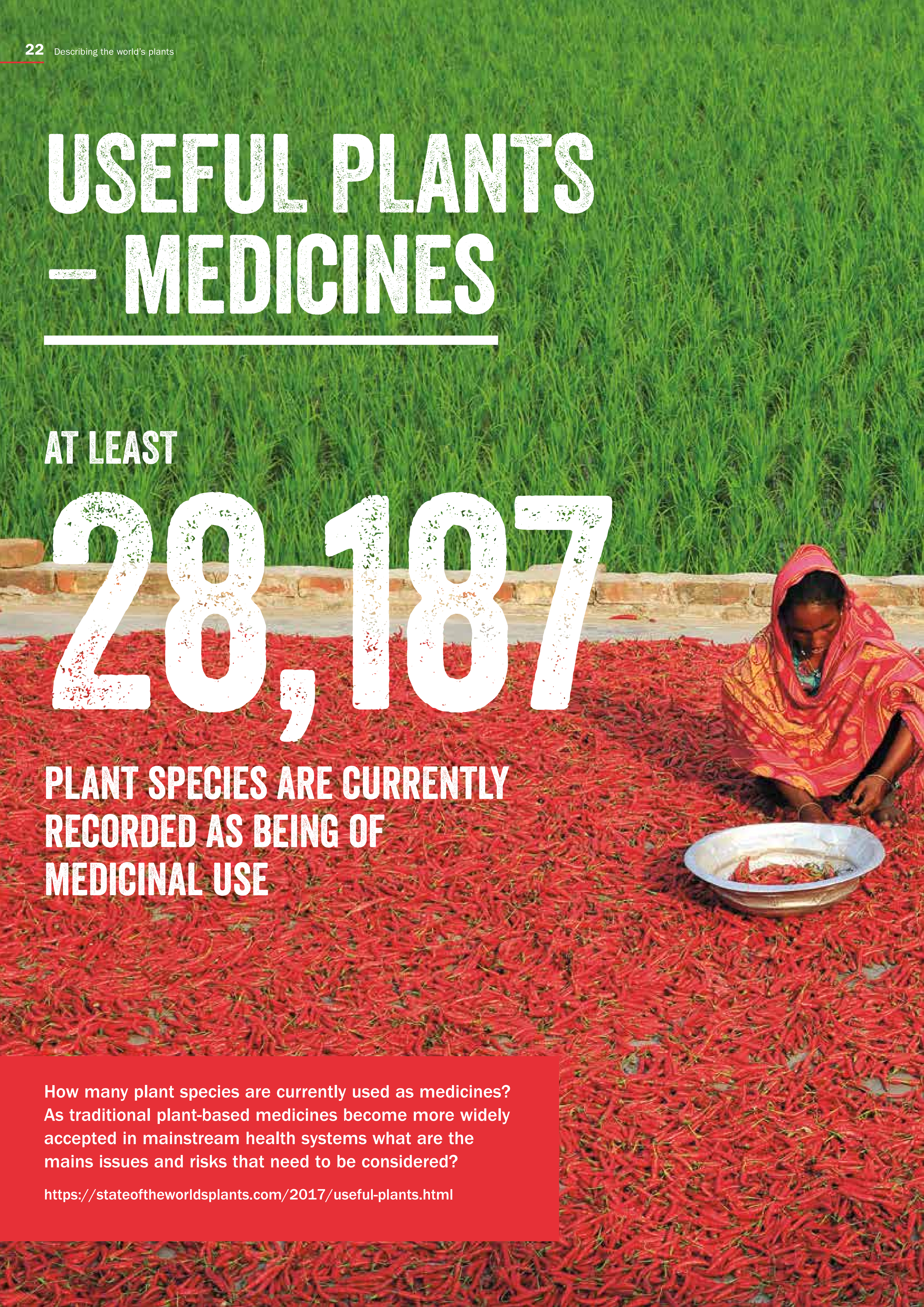
BOX 1: THE DISTRIBUTION OF SPECIES WITH SEQUENCED GENOMES ACROSS THE PLANT TREE OF LIFE IS HIGHLY UNEVEN



Among seed plants, less than half (i.e. 44%) of the angiosperm orders and only a third (33%) of gymnosperm orders have species with whole genome sequences; even some of the most species-rich angiosperm families such as Asteraceae (Asterales) and Orchidaceae (Asparagales), each with over 28,000 species, have just one or a few species with such data. In part, this reflects the previous and current focus on major crops and their wild relatives (particularly in the grass family within Poales), and on *Arabidopsis thaliana* and its relatives within Brassicales. Nevertheless, this situation is changing with the recent and rapid expansion of whole genome sequencing projects that cover a much greater evolutionary diversity of species than previous projects. The exciting challenge for the future will be to enhance our understanding of how plants function, interact and evolve, by increasing the representation of species with whole genome sequences right across the plant tree of life.

BOX 2: PLANT SCIENTISTS TAKE GENOMICS INTO THE FIELD FOR REAL-TIME DNA SEQUENCING

The generation of DNA sequence data has hitherto been restricted to high-tech laboratories, where a diverse array of sophisticated, expensive equipment is available under highly controlled conditions. This has limited the analysis of certain types of specimens for sequencing (e.g. those that cannot be moved for legal reasons such as the Convention on International Trade in Endangered Species, or which decay too rapidly). Recent technological advances suggest this is likely to change with the development of new DNA sequencing approaches and machines which are so small they can fit into the palm of your hand and can be plugged into a USB port of any portable computer[53]. The small size and robustness of such a machine means that it can sequence DNA in the field, with the potential to revolutionise the way species are identified and analysed by non-experts. Indeed, that potential is starting to be realised, as was demonstrated in 2016 when scientists at RBG Kew set up a mobile tent lab in the mountains of North Wales, extracted DNA from the local plants and used a palm-sized MinION® (see right) to sequence their DNA.



USEFUL PLANTS – MEDICINES

AT LEAST

28,187

PLANT SPECIES ARE CURRENTLY RECORDED AS BEING OF MEDICINAL USE

How many plant species are currently used as medicines? As traditional plant-based medicines become more widely accepted in mainstream health systems what are the mains issues and risks that need to be considered?

https://stateoftheworldsplants.com/2017/useful-plants.html

FEWER THAN 16% (4,478) OF THE SPECIES USED IN PLANT-BASED MEDICINES ARE CITED IN A MEDICINAL REGULATORY PUBLICATION.

In many regions of the world, people still rely on traditional plant-based medicines for their primary healthcare[1,2]. This is especially true for many rural communities in Africa, parts of Asia, and Central and South America, where plants and knowledge of their traditional use are accessible and affordable. In other countries, many of these traditional plant-based medicines are being integrated through regulations into mainstream health systems[3,4]. For example, in December 2016 the Chinese government announced their aim to integrate Traditional Chinese Medicine (TCM) into their healthcare system by 2020[5], recognising improved scientific understanding of the plants and their value in treating chronic conditions. In Europe, there is also a trend towards using traditional plant-based ('herbal') medicines alongside pharmaceutical drugs; in Germany, for example, it is estimated that 90% of the population use herbal medicines[2].

Precise figures for the value of international trade in medicinal plants are difficult to obtain[6,7], but it is clear that the industry is growing fast[8,9]. In 2000, US$17 billion was spent in the US on traditional herbal medicines. In 2003, the World Health Organisation estimated the annual global market for herbal medicines to be worth US$60 billion[2] and by 2012 the global industry in TCM alone was reported to be worth US$83 billion[4].

In this chapter we examine the regulation of these herbal medicines and the importance of having an accurate plant species name linked to them. The need for more research evaluating the medicinal properties of these plants is also covered, as well as their potential as new drugs.

REGULATION OF MEDICINAL PLANTS AND THEIR NAMES

Although herbal medicines are becoming increasingly popular in the West[4], not all are safe, and health regulators seek to control their sale and ensure appropriate quality control. Many countries publish 'pharmacopoeias', which are official publications providing precise detailed descriptions and tests to identify and assess the quality of plants used in herbal drugs. The number of plants covered by pharmacopoeias, however, represents only a small percentage of the diversity used in traditional plant-based medicines (see Box 1). Kew's Medicinal Plant Names Services (MPNS, see Box 2), collated information on the names of 28,187 species recorded as being used medicinally but found that only 4,478 are cited in regulatory publications[10].

AN INDICATION OF THE GROWING VALUE OF INTERNATIONAL TRADE IN HERBAL MEDICINES

Estimated value of herbal medicines in the US in 2000

Estimated global value of herbal medicines in 2003

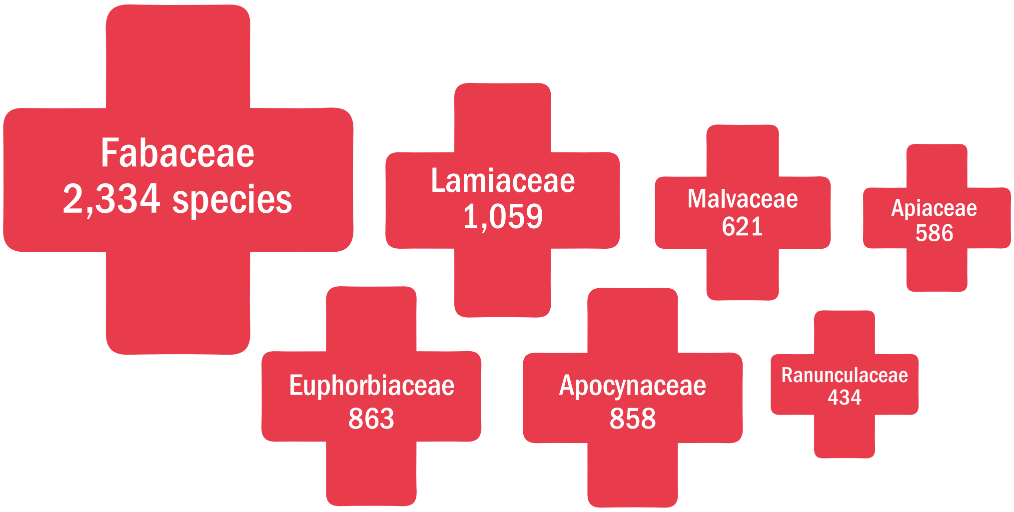
Estimated global value of TCM in 2012

BOX 1: HOW MANY MEDICINAL PLANTS ARE THERE?

The low number of plant species covered by official pharmacopoeias reflects the globalisation of a narrow range of species for use in herbal drugs. For example, in the Brazilian Pharmacopoeia the number of native Brazilian plant species decreased from 196 in the 1926 edition, to 32 in 1959, to 4 in 1977, before increasing again to 11 in 1996[11]. In addition, although the 2010 edition cites 65 species, most are European or Asian plants, with only 14 being native to Brazil[10]. A similar trend is also observed in the British Pharmacopoeia[12]. The increasing popularity of TCM and Ayurvedic medicine (a form of traditional medicine in India) in the West has led to some of the plants used in these medicines being included in pharmacopoeias[12], although globally the number of these species covered by formal monographs remains low. In China, for example, 10,000–11,250 species (c.34% of the native flora) have documented medicinal uses[13,14], but only 563 are cited in the Chinese Pharmacopoeia[10].

TABLE 1: MEDICINAL PLANT FAMILIES AND THEIR CHARACTERISTIC COMPOUNDS

Twelve of the 20 largest plant families have a significantly higher proportion of medicinal plants than would be anticipated if distribution across families were even. Here is a more detailed look at the top seven.



FAMILY	COMMON FAMILY NAME	TOTAL NUMBER OF SPECIES	NUMBER OF MEDICINAL SPECIES IN MPNS	MEDICINAL SPECIES AS % OF TOTAL	KEY CLASS OF COMPOUNDS FOUND IN MANY MEDICINAL SPECIES IN EACH FAMILY
Fabaceae	pea and bean	20,856	2,334	11.2	**alkaloids**
Lamiaceae	mint	7,756	1,059	13.7	**terpenes**
Euphorbiaceae	spurge	6,407	863	13.5	**diterpenoids**
Apocynaceae	dogbane	6,341	858	13.5	**cardiac-glycosides**
Malvaceae	mallow	5,329	621	11.7	**organic acids**
Apiaceae	parsley or carrot	4,079	586	14.4	**coumarins**
Ranunculaceae	buttercup	3,640	434	11.9	**alkaloids**

BOX 2: MEDICINAL PLANT NAMES SERVICES (MPNS)

The MPNS has collated more than 530,000 data records containing the scientific, pharmaceutical and common names used to refer to medicinal plants found in 143 sources, including pharmacopoeias, medicinal plant dictionaries, databases, publications and health regulations. The resource contains the trade forms and the plant parts cited in each of the references included (for sources see online supplementary material).

Users of the MPNS online portal can search using a herbal drug name familiar to them to find a specific medicinal plant, locate all relevant references (regardless of the names used in that reference) and discover how it is named in other references and pharmacopoeias[10].

Correct labelling is also important. Product labelling is frequently misleading, with the trade name 'ginseng', for example, referring to 15 different species of plant, each with its own particular chemistry and therapeutic properties[10]. Substitution by a Belgian clinic of one Chinese medicinal herb ('Fang Ji') with another sharing the same name, led to over 100 patients requiring kidney dialysis for the remainder of their lives[15]. For another example, see Box 3.

Robust authentication of plant ingredients included in herbal products is also vital, along with their substitutes and adulterants[16]. A recent publication of 300 internationally traded Chinese medicinal plants[17] addressed this need by presenting illustrations and detailed descriptions of source plants and trade forms, enabling comparison with their common substitutes, adulterants and counterfeits. Going forward, adulteration could be reduced by sourcing plants from sustainable resources or cultivation[18] combined with reliable traceability procedures and effective authentication and quality control[17,19].

MEDICINAL PLANTS AND DRUG DEVELOPMENT

Historically, plants have often been selected for drug development programmes because they contain specific classes of compounds, such as alkaloids and terpenoids, that are known to be biologically active, or because of their traditional medicinal uses. To what extent does family membership influence the likelihood of a species having a medicinal use? For this year's *State of the World's Plants,* we carried out an analysis of the families of 28,187 species covered by MPNS to identify the families with the highest proportion of medicinal plants (See Table 1; Figure 1). From this it is apparent that some families contain significantly more medicinal plants than might be expected. Selecting families with a high number of medicinal plants along with classes of medicinally active compounds could possibly serve as a signpost for future drug discovery programmes (see Box 4).

Plants with known medicinal uses have been a source of vital pharmaceutical drugs for the treatment of many diseases (see Boxes 5 & 6). For example, artemisinin (discovered in *Artemisia annua*) and quinine (from *Cinchona officinalis*), together with their synthetic analogues, remain among the most important weapons in our arsenal against malaria[20,21], of which 214 million cases and 400,000 deaths were recorded in 2015[22].

Will the next lead come from one or more of the 1,200 species used to treat malaria[23]? In Ghana, Nigeria, Mali and Zambia, about 60% of childhood malaria cases are first treated with herbal remedies[22]. Reviews from Cameroon and Guinea reported use of 217 and 113 species respectively[24], many proving to have antimalarial properties when tested. Of 24 species from one Latin American tree genus (*Aspidosperma*) tested in the laboratory, 19 showed activity against the *Plasmodium* malaria parasite[25]. As antimalarial drug resistance spreads[26], exploring and exploiting such under-utilised (and often under-researched) resources remains a high priority for science[27]. Success will depend both on equipping laboratories in endemic regions and establishing multidisciplinary research networks to bring together the diverse expertise necessary[28].

BOX 3: THE SIGNIFICANCE OF AMBIGUOUS LABELLING FOR PUBLIC HEALTH

Confusion about plant names may arise even in regulations intended to ensure the quality and improve the safety of herbal medicines[36,37]. A single pharmaceutical name (e.g. 'Cimicifugae Rhizoma') can be used to cover different species by different pharmacopoeias – for example, it relates to four species of *Actaea* in the *Japanese Pharmacopoeia* and one in the *European Pharmacopoeia* (see below).

MPNS enables medicine regulators to now link all these names together via an ISO standard for medicinal products[38,39].

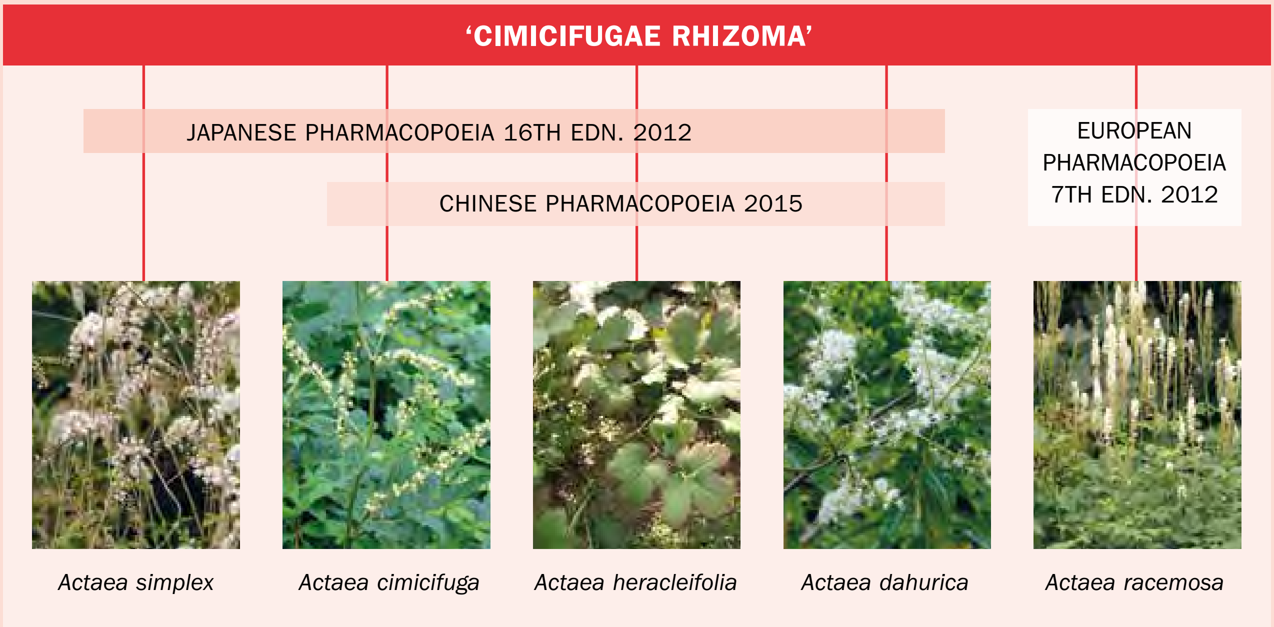


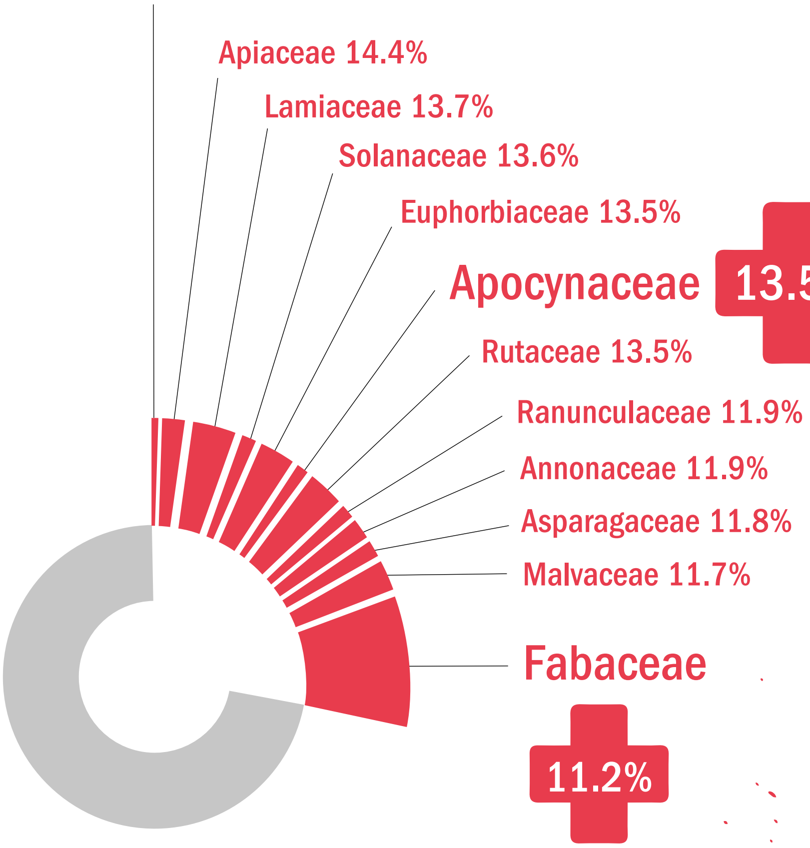
FIGURE 1: THE 12 PLANT FAMILIES WITH A SIGNIFICANTLY HIGHER PROPORTION OF MEDICINAL PLANTS THAN EXPECTED

Moraceae

22.5%

% of species in family used for medicinal purposes

Mulberry (*Morus* spp.) in the family Moraceae, contains imino sugars used in the study of diabetes



The anti-cancerous drugs **vincristine** and **vinblastine** are derived from the Madagascar periwinkle, *Catharanthus roseus* in the Apocynaceae family

The blood thinning drug **warfarin** is derived from a coumarin from sweet clover, *Melilotus officinalis,* in the Fabaceae family

There are 416 families of flowering plants (APG IV); of the 20 largest, 12 demonstrate a higher than normal percentage of species with a medicinal use. (The size of the red segment indicates the relative number of species in each family – see Table 1.)

Three noteworthy families for medicinal plants are Moraceae, Apocynaceae and Fabaceae – drugs in these families that are particularly important are shown in the schematics.

143 DATABASES AND PUBLICATIONS CITE 415,180 UNIQUE NAMES FOR PLANT-BASED MEDICINES– AN AVERAGE OF 15 ALTERNATIVE NAMES FOR EACH SPECIES

BOX 4: PLANTS AS A SOURCE OF PHARMACEUTICAL DRUGS

Since 1981, 1,130 new therapeutic agents have been approved for use as pharmaceutical drugs, of which 593 are based on compounds from natural sources. Thirty-eight are derived from medicinal plants[40,41].

Fifteen of the 56 natural drugs registered for the treatment of cancer since 1980 are derived from medicinal plants with a long history of traditional use. For example, drugs based on Paclitaxel have been isolated from the yew tree (*Taxus* spp.), Camptothecin from the happy tree (*Camptotheca acuminata*) and Podophyllotoxin from the May apple (*Podophyllum hexandrum* and *P. peltatum*).

CONSERVATION OF MEDICINAL PLANTS

Increasing demand for herbal medicines (particularly for species covered by pharmacopoeias) threatens wild populations of many of these plants[29]. Of the 28,187 species recorded in MPNS, c.1,280 are under protection according to CITES (see chapter 12)[10,30]. The commercial value of particular herbal products leads to scarcity of populations of the species used in the product. This in turn increases the frequency of species substitution – when the species is, deliberately or otherwise, substituted with a different species – and thereby threatens patient safety[17,31–34].

For example, supply shortages of *Eleutherococcus nodiflorus* ('Wu Jia Pi'), widely used in TCM to treat musculoskeletal pain and swelling[35], frequently result in its substitution with a similar-looking adulterant from the unrelated species *Periploca sepium*, which in inappropriate dosages, is toxic[17].

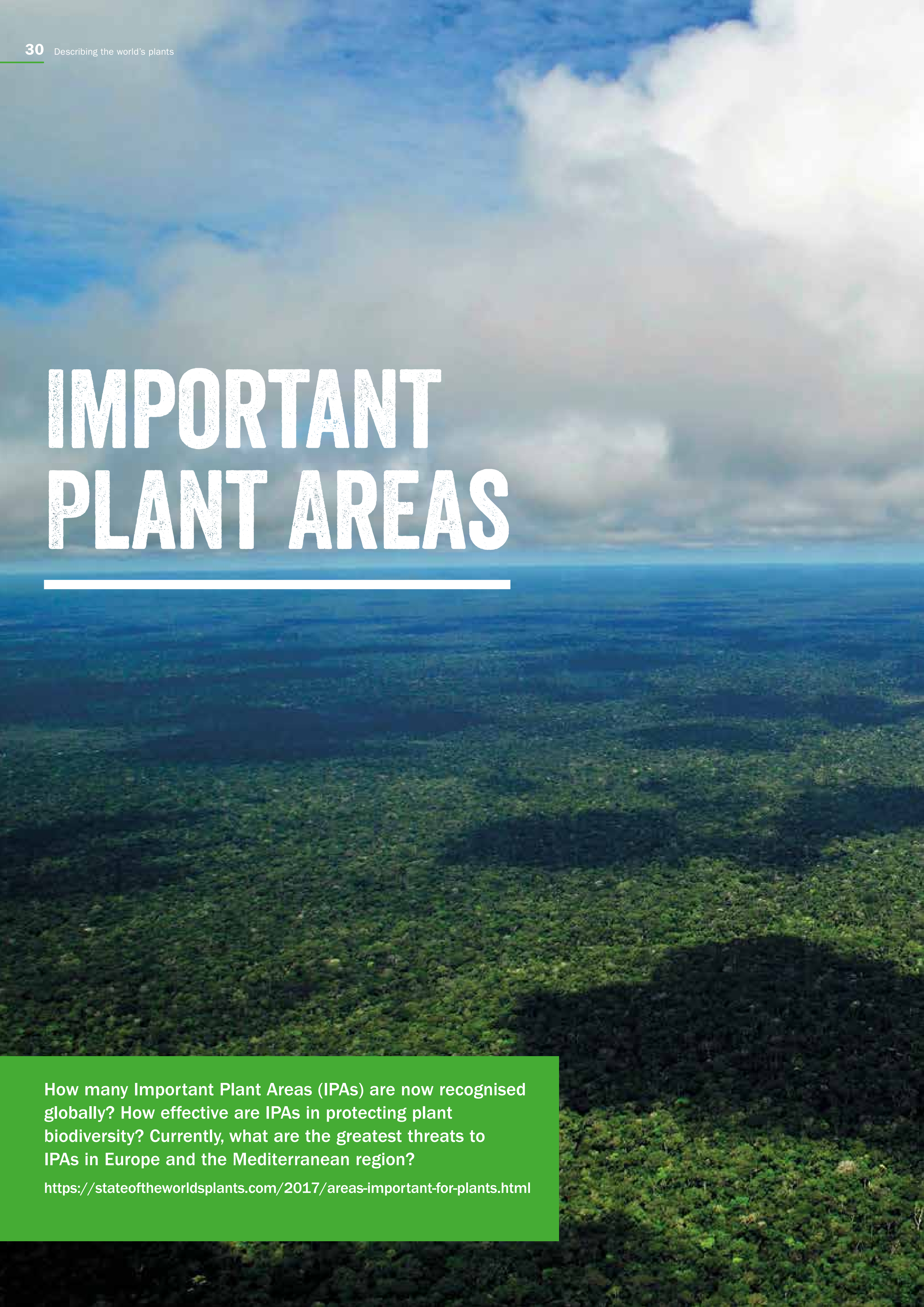
In summary, the focus of world trade on relatively few species of medicinal plants leads to sustainability and conservation issues, which ultimately lead to other plants being substituted, with potential risks to human health. More effective regulation can be achieved through more precise use of scientific plant names and greater awareness of the many alternative synonyms in use. However, clarity on which plants have or have not been studied in drug discovery programmes is also needed. This is now becoming possible through the collation of global data sources on medicinal plants and 'big data' analytics. Such approaches will be hugely important in improving our ability to realise current and future medicinal benefits from plants.

BOX 5: PLANTS AND DEMENTIA

Dementia affects 47.5 million people worldwide, with Alzheimer's disease causing most cases[42]. Of only five drugs developed specifically for the symptomatic treatment of Alzheimer's disease, two are derived from plants[43]. Galantamine, from *Galanthus* (snowdrops), *Leucojum* (snowflakes) and *Narcissus* (daffodils), was the first natural product drug to treat dementia symptoms. The second was Rivastigmine, which is chemically derived from physostigmine, an alkaloid from *Physostigma venenosum* (calabar bean)[44]. A survey of 139 different plant-derived compounds with potential to target dementia symptoms, revealed the majority (43%) to be classed as alkaloids[45]. Another study documented 152 plants with traditional uses for age-related brain diseases[46]. Research continues to provide a scientific basis to explain the traditional and potential uses of medicinal plants for dementia[47].

BOX 6: PLANTS AND DIABETES

Diabetes affects an estimated 422 million adults and is a global health and economic burden[48]. One study documents 656 flowering plant species used traditionally for diabetes, representing 437 genera and 111 families[49]. When these data were superimposed onto genetic relationship data (a phylogeny), a high proportion tended to be clustered in certain closely-related plant families[49]. Of 104 plants used for diabetes in seven Central American countries, 16 showed experimental evidence that could explain their traditional use[50]. In drug discovery, *Galega officinalis* (goat's rue) provided a useful compound for the design of the antidiabetic drug Metformin[49,50], while another plant used traditionally for diabetes, *Stevia rebaudiana* (sweetleaf), is a source of sweetener compounds used in the food industry[51].



IMPORTANT PLANT AREAS

How many Important Plant Areas (IPAs) are now recognised globally? How effective are IPAs in protecting plant biodiversity? Currently, what are the greatest threats to IPAs in Europe and the Mediterranean region?

https://stateoftheworldsplants.com/2017/areas-important-for-plants.html

THERE IS ONLY

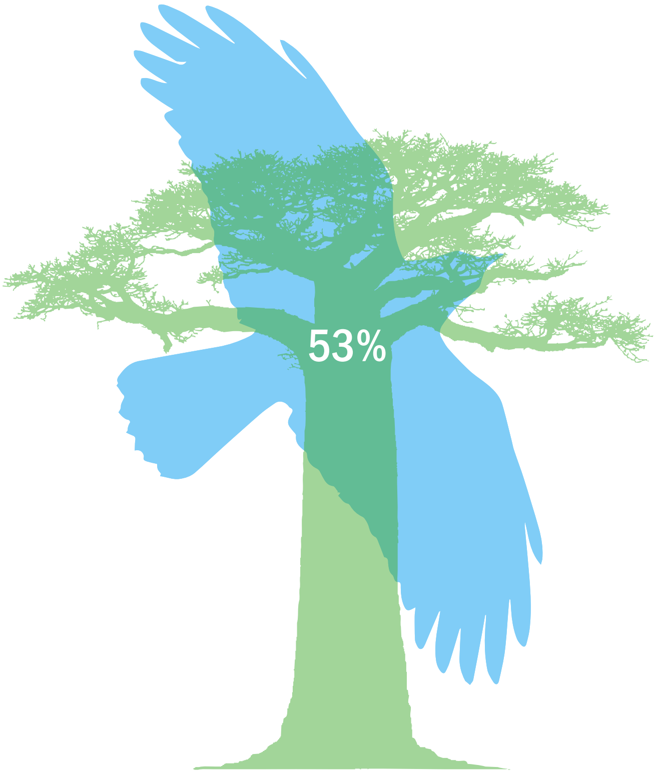
53%

OVERLAP BETWEEN IMPORTANT PLANT AREAS AND IMPORTANT BIRD AND BIODIVERSITY AREAS ACROSS EUROPE AND THE MEDITERRANEAN REGION

IMPORTANT PLANT AREAS (IPAS) INCLUDE REGIONS OF INTERNATIONALLY SIGNIFICANT POPULATIONS OF THREATENED PLANT SPECIES, THREATENED HABITATS, AND/OR AREAS THAT EXHIBIT EXCEPTIONAL BOTANICAL RICHNESS.

In total, nearly 2,550 IPAs have been either fully or provisionally identified and published to date[1]. This year we look at the effectiveness of the IPA initiative in protecting plant biodiversity, using sites in Europe and the Mediterranean region as a case study. We examine the level of protection these sites now have, and how areas identified as IPAs overlap with other site-based prioritisation initiatives, including Important Bird and Biodiversity Areas (IBAs) and Key Biodiversity Areas (KBAs). We then examine the nature of current and future threats that these IPAs face and consider the additional measures that are needed in order to ensure a positive outcome for plant biodiversity conservation into the future.

FIGURE 1: SCHEMATIC TO INDICATE THE OVERLAP OF IMPORTANT PLANTS AREAS WITH IMPORTANT BIODIVERSITY AND BIRD AREAS IN EUROPE AND THE MEDITERRANEAN REGION



HOW EFFECTIVE IS THE MANAGEMENT AND PROTECTION OF IPAS IN EUROPE AND THE MEDITERRANEAN REGION?

IPAs have been documented for 27 countries across Europe and the Mediterranean region[2–4]. Analysis of IPA data against the World Database of Protected Areas[5] revealed that 85% of IPAs in the region have some formal protection in at least a portion of the site. These high levels of overall protection align well with the Global Strategy for Plant Conservation (GSPC) Target 5: protection for at least 75% of the most important areas for plant diversity in each ecological region in the world. Some notable successes in increased protection for IPAs have been achieved within the last decade; for example, in 2010 only 18 (19%) of the 97 IPAs in Croatia were protected, whereas this figure is now 90 IPAs (93%). However, levels of protection vary widely between countries: in the United Kingdom nearly all IPAs (162 of 164 sites) have some form of legal protection, whereas outside the EU, particularly in North Africa and the Middle East, this can fall below 50%.

An analysis of the same IPA dataset against the distribution of IBAs[6] reveals that on average only 53% of IPAs overlap with one or more IBAs (Figure 1), with no one country exceeding 75%. Therefore, while there is good congruence between important sites for plants and birds in many cases, these findings indicate the clear need to assess multiple groups of organisms in site-based prioritisation schemes, as over-reliance on one dataset will result in globally important sites being omitted (see Box 1 and Box 2).

THREATS TO IPAS IN EUROPE AND THE MEDITERRANEAN REGION

An integral part of the IPA assessment process is documenting the threats impacting each site. Threat information is available for 1,518 IPAs across Europe and the Mediterranean region, of which 1,092 have a broad measure of threat impact (high, medium, low)[1] (see supplementary material). Almost 95% of IPAs are affected by at least one threat category, with 60% (658 IPAs) experiencing at least one high-impact threat. Many IPAs are also impacted by multiple threats: nearly 50% have four or more associated threats, although only 7% have four or more high-impact threats (see Table 1).

Threats vary widely between IPAs but some interesting trends across Europe and the Mediterranean are evident (Table 1). Development and construction is the largest class of threat, but it is noteworthy that the most damaging form of development across the region is from tourism and recreation, impacting 595 IPAs in total – 136 with high impact (see Box 2). This can range, for example, from the disturbance and trampling of sensitive habitats by excessive recreational visitors, as at the Marele Grohotis IPA in the Piatra Craiului National Park of Romania, to the widespread destruction of habitat for tourist resort development, as in the Western Mediterranean Coastal Dunes IPA in Egypt. This highlights the urgent need for rigorous Environmental Impact Assessments of proposed tourism developments.

BOX 1: IPAS, IBAS AND KBAS IN TURKEY[7]

Co-occurrence of IPAs with conservation prioritisation measures for other taxonomic groups, such as IBAs or KBAs, can bolster the case for their protection. In Turkey, 62% of IPAs overlap with IBAs, and 79% with KBAs – the latter figure being higher because plant data were included in the KBA assessments. For example, Acigöl (Aci Lake), a shallow body of saline and fresh water in south-west Turkey, is an IPA on the basis of regionally threatened salt steppe habitats and the presence of six globally threatened endemic plants. The site is also an IBA, as it supports internationally important breeding populations of wetland and steppe birds, including the globally threatened Great Bustard (*Otis tarda*)[12]. However, there are some areas where IPAs and IBAs have lower congruence. For example, many freshwater IBAs in Turkey, which have been classified as such because of their importance for migratory and breeding birds, have low plant diversity and a predominance of widespread, well-dispersed species. The Büyükçekmece Lake near Istanbul is a good example of this; it qualifies as an IBA because of its large number of wintering waterfowl, but is not an IPA.

BOX 2: IPAS UNDER THREAT – THE CASE OF POODRI, CZECH REPUBLIC

The alluvial wetland region of Poodri, along the Odra River floodplain in the Czech Republic, is designated an IPA primarily on the basis of the presence of 14 regionally threatened habitats, including large extents of natural eutrophic lakes, lowland hay meadows, and alluvial and riparian forests. It is a site of international conservation importance, with multiple protected area designations including Ramsar Site, Protected Landscape Area and National Nature Reserve, as well as IBA and KBA status[8, 13]. Despite this, threat assessments made at the time of IPA designation indicate that Poodri has at least 23 threat factors, of which 9 are classified as high impact. These include eutrophication and waterway management, but as with many IPAs within Europe, Poodri is under greatest threat from development, including for tourism and recreation, as well as the abandonment of traditional land use practices.

PAS AND KBAS IN THE CZECH REPUBLIC, SHOWING THE LOCATION OF THE HIGHLY THREATENED POODRI SITE

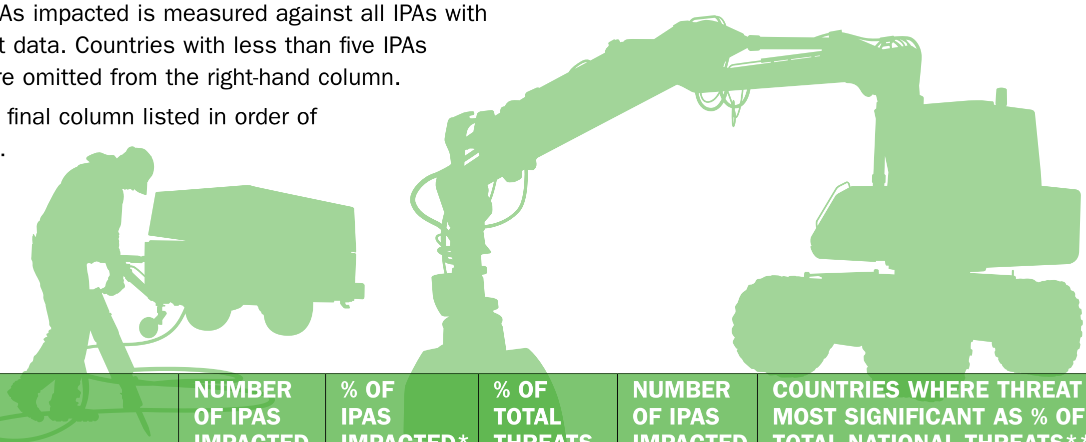
🟦 KBA Poodri
🟦 KBA
× IPA

KBA data from Birdlife International and Conservation International[6]

TABLE 1: THE MOST SIGNIFICANT THREAT CATEGORIES IMPACTING IPAS IN EUROPE AND THE MEDITERRANEAN REGION

*Per cent of IPAs impacted is measured against all IPAs with available threat data. Countries with less than five IPAs documented are omitted from the right-hand column.

**Countries in final column listed in order of %, highest first.

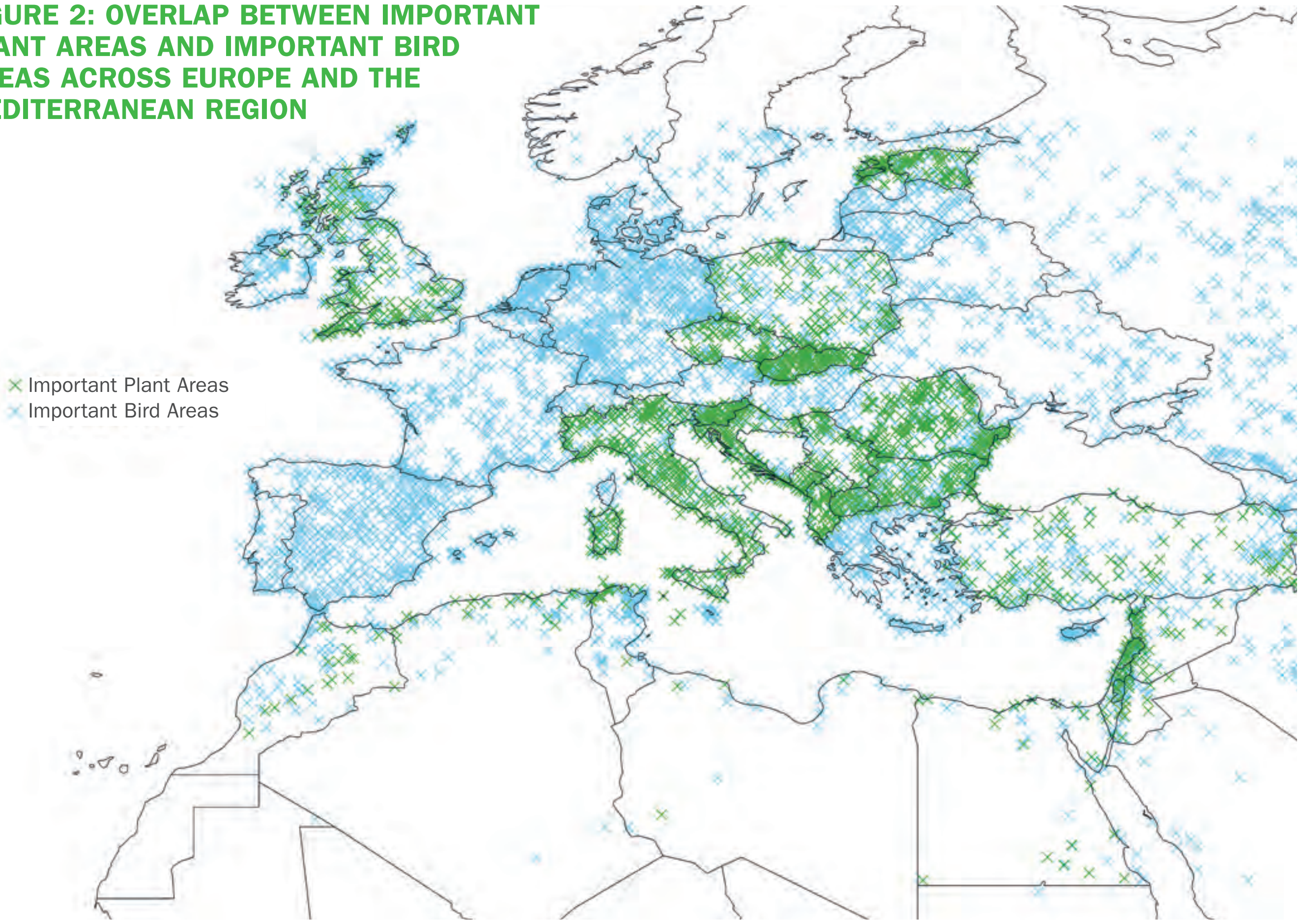


THREAT CATEGORY	NUMBER OF IPAS IMPACTED	% OF IPAS IMPACTED*	% OF TOTAL THREATS TO IPAS	NUMBER OF IPAS IMPACTED AT HIGH LEVEL	COUNTRIES WHERE THREAT IS MOST SIGNIFICANT AS % OF TOTAL NATIONAL THREATS**
Development & construction (recreation/tourism)	595	40.2	9.7	136	Ukraine, Slovenia, Montenegro, Estonia, Lebanon, Romania
Land abandonment/ reduced management	426	28.8	6.9	152	Croatia, Ukraine, Estonia, Slovenia, United Kingdom, Slovakia
Agricultural intensification/ expansion (grazing)	402	27.2	6.5	65	Morocco, Albania, Syria, Algeria, Tunisia, Israel
Inappropriate forest management (intensified forest management)	310	20.9	5.0	71	Macedonia, Estonia, Slovakia, Poland, Bulgaria, Czech Republic
Inappropriate forest management (deforestation)	269	18.2	4.4	67	Morocco, Albania, Montenegro, Macedonia, Lebanon, Romania
Development & construction (urbanisation)	265	17.9	4.3	46	Israel, Lebanon, Slovenia, Montenegro, Croatia, Poland
Habitat fragmentation	264	17.8	4.3	71	Israel, Slovakia, United Kingdom, Albania, Czech Republic, Macedonia
Development & construction (infrastructure/transport)	251	17.0	4.1	40	Poland, Montenegro, Slovenia, Estonia, Egypt, Macedonia
Invasive species (plants)	251	17.0	4.1	55	United Kingdom, Czech Republic, Slovakia, Ukraine, Montenegro, Croatia
Inappropriate forest management (afforestation)	248	16.8	4.0	41	Ukraine, Slovakia, Estonia, Turkey, Romania, Czech Republic

BOX 3: CULTURAL LANDSCAPES – ABANDONMENT OF TRADITIONAL HAY FARMING PRACTICES AND THE THREAT TO IPAS

IPA data indicate that land abandonment and reduced habitat management are also significant threats to plant diversity in parts of Europe and the Mediterranean region, affecting 426 IPAs and having a high impact on 152 sites. Abandonment of traditionally-farmed landscapes in Europe has been a marked phenomenon over recent decades, particularly in agriculturally marginal land[9]. Some of the most important habitats for biodiversity in Europe are the result of a long-term relationship between traditional farming practices and wild flora and fauna, sometimes spanning centuries. Such practices can promote a wealth of semi-natural microhabitats[9,10].

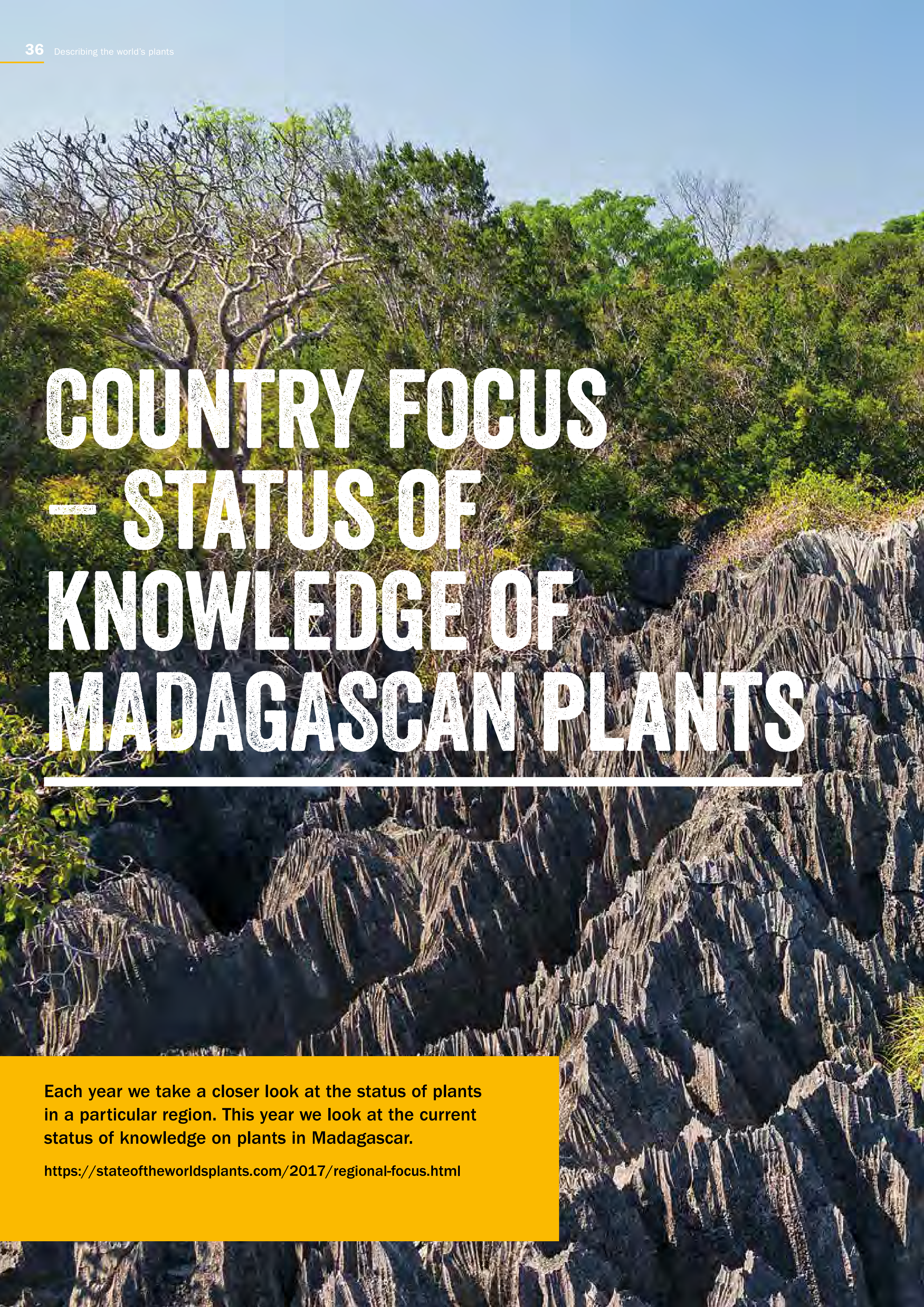
FIGURE 2: OVERLAP BETWEEN IMPORTANT PLANT AREAS AND IMPORTANT BIRD AREAS ACROSS EUROPE AND THE MEDITERRANEAN REGION



Adverse forest management practices are the second major threat; this includes both habitat destruction through deforestation, and habitat conversion through afforestation, typically for commercial timber and other wood products. The third major threat is agricultural intensification and expansion, particularly in North Africa and the Middle East where increased grazing pressure from domestic herds is the primary threat category, with 67% of IPAs impacted[3]. Conversely, the species-rich hay meadows of Eastern Europe are well represented in the IPA network – for example in Croatia. Human intervention, through community-led restoration of traditional farming, is being practised in some areas in order to restore the plants (see Box 3). The opposite situation occurs in the tropics, where species-rich rainforests are of greatest conservation value[9] and land abandonment can lead to rapid and marked increases in species diversity, with benefits obtained from these secondary forests for both biodiversity and effective carbon storage[11]. Hence, threat categories for IPAs are very region-specific and highlight the importance of understanding the historical context and baseline biodiversity for each site.

In summary, the preliminary assessment carried out for this year's *State of the World's Plants* reveals good levels of success with the designation and formal protection of IPAs in Europe and the Mediterranean region. Hence there is, on a regional basis at least, cause for some optimism for plant conservation and achieving GSPC Target 5, although it remains to be seen if this pattern is similar across the other global sites, including the Kew-led Tropical Important Plant Areas. An ongoing issue, however, is the lack of congruence between different formal protection initiatives and their effective management. Despite plants driving the ecosystems that support faunal assemblages, most protected areas were not originally established with plant conservation as a focus. Consequently, many are not managed for their plants, and the key challenge is to ensure protected area initiatives enable better management for the species and habitats highlighted in the IPA assessments[1,4]. A further pressing need is to increase the connectivity of natural habitat in the landscape between these important sites, in order to increase resilience to biodiversity loss in the face of climate change; this is particularly challenging in fragmented and transformed landscapes, where maintaining biodiversity corridors is essential to reducing the risk of plant diversity loss.[14].

TOURISM IS ONE OF THE GREATEST THREATS TO IMPORTANT PLANT AREAS IN EUROPE AND THE MEDITERRANEAN REGION



COUNTRY FOCUS – STATUS OF KNOWLEDGE OF MADAGASCAN 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 Madagascar.

https://stateoftheworldsplants.com/2017/regional-focus.html

83%

OF MADAGASCAR'S 11,138 NATIVE SPECIES OF VASCULAR PLANT OCCUR NOWHERE ELSE ON EARTH

THE WORLD'S FOURTH LARGEST ISLAND IS HOME TO FIVE UNIQUE PLANT FAMILIES[1] AND THREE TIMES AS MANY PALM SPECIES AS CONTINENTAL AFRICA[2].

Madagascar is home to 11,138 native species of vascular plant, and 83% occur nowhere else on earth. In addition, at least 546 non-native introduced species are known to be naturalised[3]. The continually updated Madagascar Catalogue[4] presents summary figures for plant diversity on Madagascar up until 2012, and 299 new species have been described since then[5]. Following IUCN criteria, 1,676 out of approximately 4,200 endemic species assessed are judged to be at risk of extinction[6].

This continental island biodiversity hotspot[7–9] is a unique laboratory of evolution whose biotic richness appears to be related to its long isolation, climatic changes over long geological timescales and habitat heterogeneity. Twenty-six per cent of the endemic plant genera are most closely related to other Malagasy lineages, 22% have floristic links with Africa, 9.1% with South-East Asia and 6.2% with India[10]. The majority of endemic genera arose in the Miocene (23 to 5.3 million years ago) or more recently. While there is a growing body of work on mechanisms underpinning faunal diversification, little comparable work has been done relating to the flora.

Habitat degradation is substantial and continuing[11], but the true extent of original forest and its subsequent loss is disputed[12,13]. Causes of habitat transformation include droughts and naturally occurring fires[14], amplified in more recent historic periods by the human introduction of cattle and the expansion of grazing[15,16].

Conservation initiatives include the trebling of the protected area network in 2006 (to protect 10% of Madagascan territory by 2010), following the 2003 Durban Vision[17]; attempts to prioritise further protected areas to maximise conservation impact[18,19]; a major regional focus by the Critical Ecosystem Partnership Fund[20]; and increasing community involvement in planning and implementation of the vision. In 2015, a major expansion of the protected areas network took the total to 123, with the protected areas encompassing significantly higher percentages of forest vegetation.

ENDEMIC PLANT FAMILIES

Five families of woody plants occur on Madagascar and nowhere else on earth, with a sixth, near-endemic family also found in continental Africa. Two of the endemic families, Sarcolaenaceae and Sphaerosepalaceae, are allied to the mallows (order Malvales). The remainder, Asteropeiaceae, Barbeuiaceae, Physenaceae, and the near-endemic Didiereaceae known for its bizarre life forms, belong to the Caryophyllales.[2]

The largest endemic family, Sarcolaenaceae, has 72 species, and is commonly encountered on the plateau. Several recently discovered species await formal description[4]. The family occurred in South Africa in the Miocene, and may have African origins[21–23]. This is also the case in the near-endemic Didiereaceae, with four iconic genera in the spiny forests of Madagascar and two in continental Africa[24]. Of the 25 species of Sarcolaenaceae assessed and available on the IUCN Red List, 15 (60%) are considered at risk of extinction[25]. The family provides a case study to test the effectiveness of the newly expanded protected areas network in conserving threatened Malagasy plant diversity[26].

PALMS

There are 204 species of palm in Madagascar[27–30], and 98% are endemic to the island. A large proportion (83%) is threatened with extinction[28–31] – this is almost four times the proportion estimated for plants globally and exceeds estimates for all other comprehensively evaluated plant groups in Madagascar. Worryingly, 28 threatened species lie outside the protected areas network. More than half of Madagascar's palm species are known from a single site or have fewer than 100 individuals in the wild[31].

The definitive *Palms of Madagascar*[32] was published in 1995, but since then an astonishing 34 species have been described and named, with more awaiting description. The spectacular new palm genus *Tahina,* with its huge 5 m fan-shaped leaves and 4–5 m high candelabra-like inflorescence, was discovered as recently as 2008 and is known from just two sites[33,34].

Ninety per cent of Malagasy palm species occur in humid forest, and the Masoala Peninsula and adjacent Makira region of north-eastern Madagascar are diversity hotspots, with 46 and 43 species respectively, including several currently new to science.[35,36]

ORCHIDS

Close to 1,000 species of orchid occur on Madagascar, with diversity concentrated in the moist eastern and northern forests[4,37]. Orchids make up just under 10% of Madagascar's native flora. Most species (90%) are endemic to the island, and 70% are likely to be threatened with extinction[38]. Many Malagasy orchid species groups are poorly understood both taxonomically and geographically and are the focus of ongoing baseline research.

Orchids need specialised symbiotic root fungi to germinate, which limits their distributions and presents difficulties for their conservation. Processing and storing orchid seed is challenging. Nevertheless, 143 species have their seeds conserved in Kew's Millennium Seed Bank and Madagascar's Silo National des Graines Forestières.

One project at Kew has studied orchids from the Itremo Protected Area in the Central Highlands of Madagascar. The research developed a method to collect and culture fungi growing within orchid roots at different stages of growth, from the earliest stage of germination to mature plants. Some of these fungi have proved to be generalist, which means they have the capability to significantly improve seed germination in a number of diverse threatened orchids with few small remaining populations.

Community projects are also under way to conserve the spectacular but Critically Endangered *Angraecum longicalcar* and *Grammangis spectabilis* through propagation, environmental protection and education programmes[39,40].

YAMS: CONSERVATION THROUGH CULTIVATION

Eighty-four per cent of Madagascar's 37 native wild species of yam occur nowhere else in the world[41]. This is almost 10% of the world's yam species[42–44].

Wild yam tubers are a key food resource in many parts of Madagascar[42,45], especially in the rainy season 'hungry gap' before annual rice harvests (usually April or May). Many species of yam have narrow distributions and a number are heavily exploited. Of the 25 species assessments of yams currently published on the IUCN Red List[25], nine (36%) are threatened and a further five (56% in total) are near-threatened.

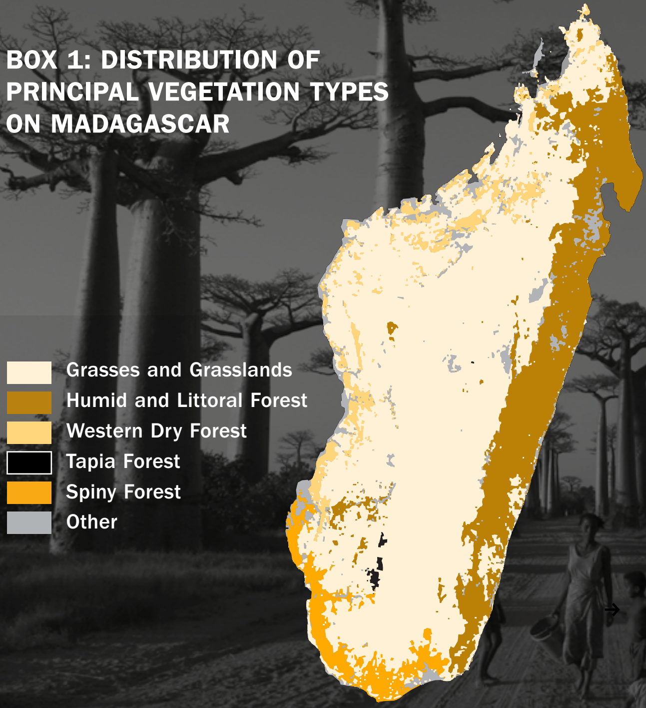
New species of edible yam are still being discovered and described. *Dioscorea irodensis*[46], known from just three localities in northern Madagascar, is provisionally assessed as Critically Endangered – its tubers are being extracted at an unsustainable rate. In a Kew project funded by the Darwin Initiative, such threatened edible species are being conserved by seed banking, germplasm collection and by community cultivation alongside non-native cultivated winged yam (*D. alata*), to improve food security and income (http://www.darwininitiative.org.uk/project/22005/). During the first 18 months of the project, 19 edible wild species have had their seed banked in Madagascar and at Kew. In addition, 13 species including *D. irodensis* are now part of community cultivation initiatives involving 3,000 households in Madagascar. Conservation actions for further species will be conducted in 2017–18.

↑ **SPINY FOREST**

Spiny forest occurs in areas of south-west Madagascar with a mean annual rainfall of around 540 mm and a dry season of nine months or even more. Depending on rainfall and substrate, it varies from forest to thicket or low scrub. The Malagasy near-endemic family Didiereaceae dominates, with arborescent succulents such as *Adansonia*, *Aloe*, *Euphorbia* and *Pachypodium* forming significant elements of the flora. Most of the species are endemic to Madagascar and to this vegetation type, and many have horticultural potential.

Spiny forest covers 18,355 km², and a mere 4% was included in protected areas in 2006, rising to 34% in 2015. Spiny forest has reduced by 30% since the 1970s[55].

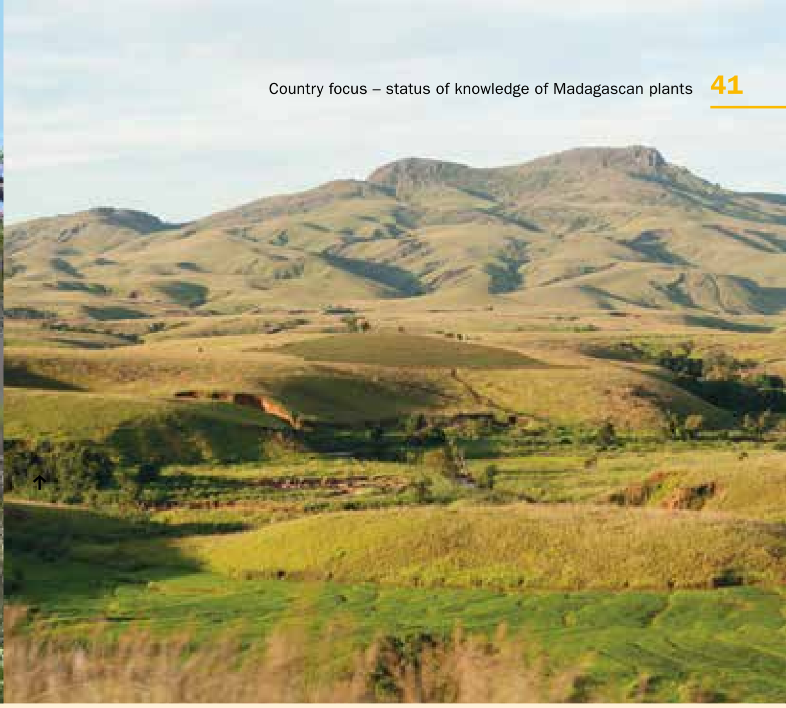
BOX 1: DISTRIBUTION OF PRINCIPAL VEGETATION TYPES ON MADAGASCAR



HUMID & LITTORAL FORESTS →

Humid and littoral forests occur in eastern Madagascar, mostly in areas with rainfall exceeding 1,500 mm per year and with a short to non-existent dry season. They are generally evergreen with a closed canopy. Much of this vegetation only remains in upland areas, with *Weinmannia* and *Tambourissa* as characteristic elements, but humid forest still extends to sea level on the Masoala Peninsula of north-east Madagascar. Dominant species vary with latitude and elevation. International trade in the highly valued and exploited Malagasy rosewood (*Dalbergia* spp.) is now controlled through CITES (see chapter 12).

Humid forest covers an area of 47,737 km². Of this, 56% now lies within the expanded protected area network of 2015, but since the 1970s its extent has reduced by 33%[55]. Littoral forest covers a mere 274 km²; it has been reduced by 23% since the 1970s and it is now highly fragmented, with 24% occurring in protected areas. A quarter (25%) of littoral forest species are endemic to this vegetation type[55,56], and vegetation on titanium-bearing sand is under particular threat because of forest clearance for this valuable mineral extraction. However, the mining company QMM has established conservation zones covering 6.2 km², and is funding habitat restoration for wetland and coastal forest in the area.



↑ WESTERN DRY FOREST

Western dry forests are found in the west and north of Madagascar, in areas with 600–1,500 mm annual rainfall and a dry season of around six months. Two of the largest remaining areas of dry forest are Ankarafantsika and Menabe. They are largely deciduous, and home to many of Madagascar's endemic woody species, including the majority of Madagascar's flagship endemic baobabs. Following the 2016 meeting of CITES Parties, international trade in Grandidier's baobab (*Adansonia grandidieri*) is now controlled due to over-exploitation, particularly of its fruit and seeds (see chapter 12).

Western dry forest covers an area of 31,970 km². Following the 2015 designations, 26% is in protected areas. However, it has suffered a 40% reduction in extent since the 1970s and is being destroyed at a faster rate than any of the other forest types on Madagascar[55].

↑ GRASSES & GRASSLANDS

Madagascar is home to 541 species of grass – 40% of these are endemic to the island[47]. Research indicates that grasses colonised Madagascar at least 97 times, mainly from tropical Africa[48], with the oldest monotypic lineage, *Lecomtella madagascariensis,* arriving more than 20 million years ago[49].

The influence of early botanical workers who argued that Madagascar was entirely forested, persists in the literature to this day[13]. Certainly, rapid human-induced transformation from forest to grassland landscapes occurred in some parts of Madagascar towards the end of the first millennium[16]. However, in recent years, research into the species of Malagasy grasslands has indicated that many of the species are in fact endemic to Madagascar, and endemic grass species continue to be discovered[50–54]. Research is in progress to distinguish between natural fire-maintained grassy biomes and ecosystems degraded through anthropogenic activity.

Grass-dominated ecosystems (including wooded grassland, tapia and palm savanna, but excluding cultivated land) now cover more than 65% of the island[55].

TAPIA FOREST →

Tapia forest occurs on the central and western plateau. The most characteristic trees are species of the Malagasy endemic families Sarcolaenaceae and Asteropeiaceae, and *Uapaca bojeri*, host plant of the culturally and economically important silk moth caterpillars.

Tapia forest covers an area of 1,319 km², but this vegetation is hard to map and figures are uncertain. It is estimated that 21% lies within the current protected area network. It is suspected that tapia forest has suffered a reduction in extent of around 43% since the 1970s[55,57].

CLIMATE CHANGE – WHICH PLANTS WILL BE THE WINNERS?

Which plant traits will enable species to tolerate both current and future climate change? Are there particular physical, physiological and/or life cycle characteristics that determine the winners?

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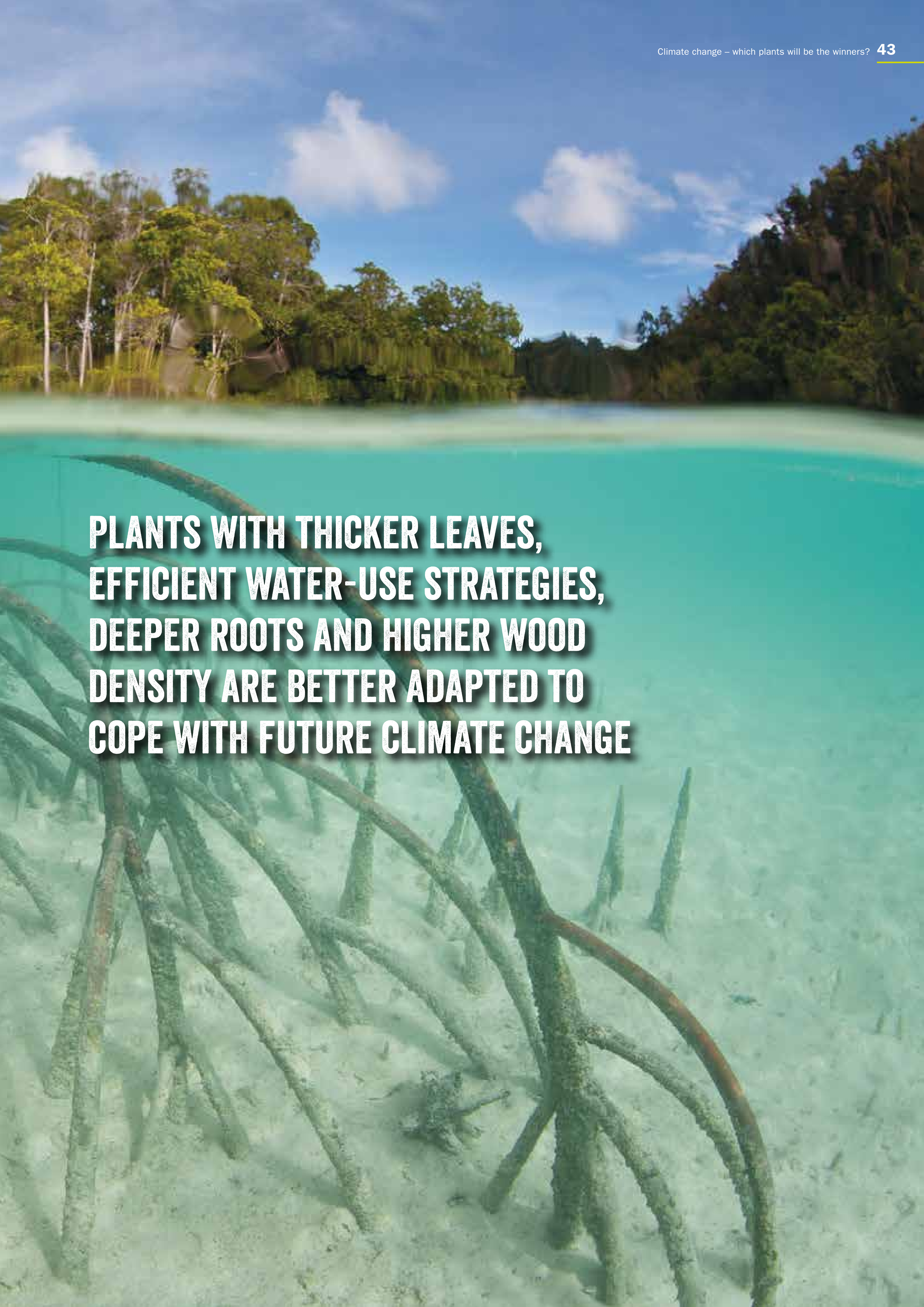


PLANTS WITH THICKER LEAVES, EFFICIENT WATER-USE STRATEGIES, DEEPER ROOTS AND HIGHER WOOD DENSITY ARE BETTER ADAPTED TO COPE WITH FUTURE CLIMATE CHANGE

PLANT RESPONSES TO CLIMATE CHANGE FOLLOW THREE MAIN TRAJECTORIES: MOVE, ADAPT OR GO EXTINCT[1–3].

As discussed in last year's *State of the World's Plants*, there is compelling evidence for all three processes starting to occur across the globe. Large-scale patterns of changing plant distributions, flowering times and novel community assemblages in response to rising temperature and changing rainfall patterns, are now apparent in many vegetation biomes. As yet, there is less evidence for climate change driven extinctions of plant species occurring, but this will almost certainly be a feature in future years if some populations are unable to move or adapt to environmental changes quickly enough.

Also highlighted in last year's report, however, is emerging evidence from various studies indicating that vegetation appears to be more resilient to climate perturbations in some regions of the world than in others[4]. Thus, the vegetation remains *in situ* with little apparent impact. One possible reason for this apparent resilience is that these regions have a higher percentage of individual species with features (response traits) that make them better able to withstand climate change.

Plant traits suggested to enable species to tolerate both current and future climate change include: physical characteristics (e.g. plant height, leaf size and rooting depth); physiological measures (e.g. respiration rate, water-use efficiency); and/or attributes associated with life history and life cycle events (such as flowering times, leaf longevity, and sexual versus asexual reproduction mechanisms). These are often referred to as 'plant functional traits'[5–7].

Determining the plant traits that allow species to cope with climate change is important because it can direct the conservation and management strategies needed to safeguard the future of rare, endangered and economically important plant species, both now and in the future. Analysis of plant traits offers a window to assess how shifts in climate will impact on different species, and hence on the diversity of plant communities, as well as enabling the identification of those plants more resilient to current and future climate change.

Over the past decade, there has been much research into plant traits, allowing better predictions for how plant biodiversity will be affected by a changing climate. This year, we have examined the emerging evidence from these studies. First, we extracted the evidence for traits that enable plant species to tolerate climate change in individual vegetation biomes. Second, we determined whether there is a subset of common traits across biomes that confer resilience to climate change globally. Finally, we asked whether the evidence to date allows us to determine clear 'winners' and 'losers' under future climate change.

Recent climate changes include the warming of the atmosphere and oceans, a reduction in snow and ice, a rise in sea level, an earlier onset of spring, and the increased frequency and intensity of extreme events[9]. Future global predictions suggest that by 2050 some terrestrial regions will see: i) increased temperature; ii) changes in precipitation (decrease in mid-latitude and subtropical dry regions; increase in high latitudes, equatorial Pacific and mid-latitude wet regions); iii) increased frequency of climate variability and extreme events; iv) increased atmospheric CO_2; and v) increased sea level rise and salinity[9]. In our review, we examined the evidence for traits that allow species to tolerate any of these five parameters of climate change. We also looked for evidence of traits that are beneficial for coping with two indirect effects of climate change – increased fire frequency and changing nitrogen availability.

A biome-by-biome literature search was conducted for 12 global vegetation biomes (Figure 2, p. 53). Studies to be included in our analysis were selected from the period 2008–17. Working sequentially back in time, we used the data in the studies to address the question 'What traits benefit species under climate change?'. We only examined native plant species in our study and did not include crops. Trait features were standardised and grouped based on Perez-Harguindeguy et al. (2013)[10], resulting in a list of 122 traits identified. In total, 257 studies were examined in detail. Of these, 108 contained examples of plant species displaying traits that may enable them to tolerate both current and future climate change. We identified the most useful traits (Figure 1), based on the largest number of papers that provided support for this trait potentially being beneficial under climate change for each biome.

1. INCREASED DROUGHT

Studies analysed highlight four key plant traits that may enable species to tolerate increased drought, as follows:

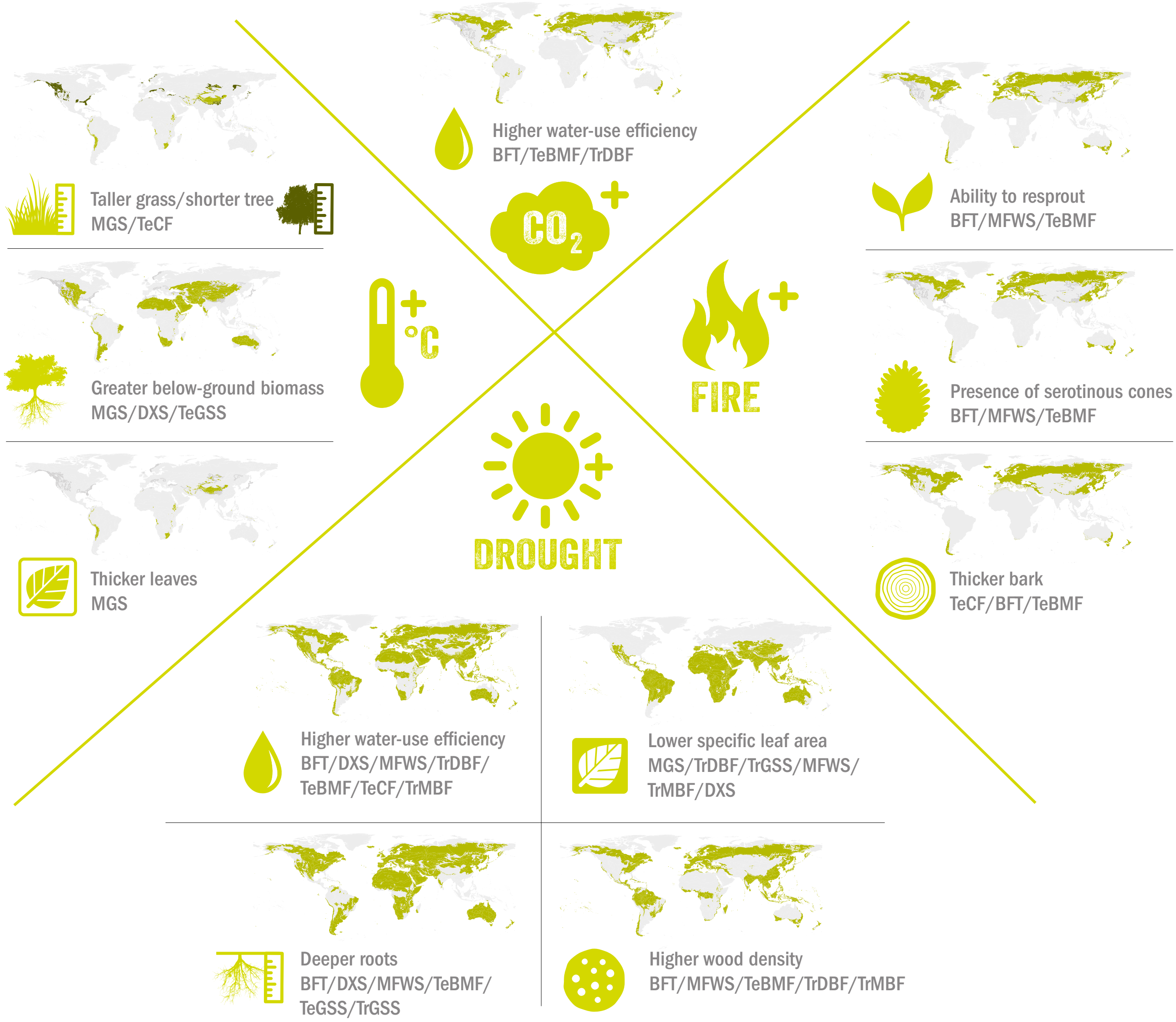
DROUGHT

Higher wood density: Theory predicts that drought will select for denser wood because this provides increased mechanical support, enabling the continued movement of water and solutes around the plant[11–12]. Studies to date show that in most forest biomes this trait does benefit plant persistence under increased drought (Figure 1). For example, in the Amazon rainforest, monitored plots showed that trees with higher wood density were less vulnerable to mortality during the 2003 drought event[13]. Furthermore, a recent large meta-analysis showed that higher wood density conferred a lower risk of mortality with drought[14]. (See Box 1.)

Lower specific leaf area (SLA): SLA is the ratio of leaf area (the area of a single leaf side) to its dry mass. Having leaves with lower values of SLA (i.e. thicker leaves with higher carbon investment) leads to increased resistance to water loss from the plant during drought. For example, studies from tropical and subtropical grasslands, savannas, and shrublands biomes show that plants with sclerophyllous leaves (hard, thick and leathery i.e. low SLA) are more able to tolerate drought[15]. (See Box 2.)

Higher water-use efficiency (WUE): WUE refers to a set of internal plant traits that allow for more frugal water use. These traits include rapid stomatal closure and the ability to maintain water-flow in the stem despite low water availability. Studies have found high water-use efficiency to be an important trait in the six forest biomes and also in the desert biome.

FIGURE 1 TRAITS THAT MAY ALLOW PLANTS TO TOLERATE DIFFERENT ASPECTS OF CLIMATE CHANGE



BIOME	
BFT	Boreal Forests/Taiga
DXS	Deserts and Xeric Shrublands
MFWS	Mediterranean Forests, Woodlands and Scrub
MGS	Montane Grasslands and Shrublands
TeBMF	Temperate Broadleaf and Mixed Forests
TeCF	Temperate Coniferous Forests
TeGSS	Temperate Grasslands, Savannas and Shrublands
TrDBF	Tropical and Subtropical Dry Broadleaf Forests
TrMBF	Tropical and Subtropical Moist Broadleaf Forests
TrGSS	Tropical and Subtropical Grasslands, Savannas and Shrublands

ANALYSIS OF PLANT TRAITS OFFERS A WINDOW TO ASSESS HOW SHIFTS IN CLIMATE WILL IMPACT ON DIFFERENT SPECIES, AND HENCE ON THE DIVERSITY AND RESILIENCE OF PLANT COMMUNITIES

Deeper roots: Deeper roots enable species to obtain water stored lower in the soil profile and therefore better tolerate drought. This trait is seen in studies across a number of biomes. For example, species from the temperate grassland biome that have deeper roots show higher survival and better recovery after a severe drought experiment[16] (see Box 3).

2. INCREASING TEMPERATURES

The second most studied driver encountered in our review was increasing temperature. The three most important traits that were found to enable species to tolerate higher temperatures were:

Plant height: This seems to be a trait that varies according to biome and closely tracks temperature and water availability, with opposing traits apparently beneficial in grasslands and forests. For example, a transplant experiment in montane grasslands in cool Norway found that taller grasses and forbs are able to tolerate warming conditions better, probably due to their advantage under increased light competition[17]. In contrast, studies in warmer tropical and subtropical moist broadleaf forests indicated that shorter trees appear to tolerate increasing temperatures, as they are better able to cope with water stress[18].

Thicker leaves: Variation in the thickness of a leaf is related to a trade-off between rate of photosynthesis (which is higher in large, thin leaves) and loss of water through transpiration (which is lower in small, thick leaves). Physiological theory predicts that thicker leaves can buffer increased variation in temperature[19]. A number of studies demonstrate that species with thicker leaves are better able to withstand increased temperatures. A study in the montane grasslands of the Caucasus, for example, demonstrated that after 25 years of increasing temperatures, those species with thicker leaves were in higher abundances[20].

Greater below-ground biomass: In three grassland biomes, studies suggest that higher root allocation is a beneficial trait under climate warming. Roots enable greater access to below-ground resources (water and nutrients); they can also function as carbon storage organs to support the next year's growth, and they can facilitate faster vegetative spread. Studies found that plants in the warmest conditions in the Mojave Desert have higher investment in roots[21], while montane grassland species have higher allocation to roots after suffering warming[20].

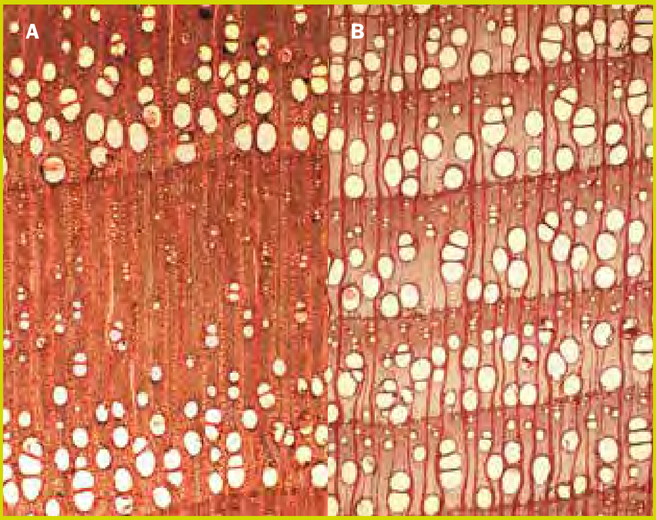
3. INCREASED FREQUENCY AND DURATION OF FIRES

Studies to date indicate three main traits that are predicted to enable species to tolerate future increases in the frequency of fires (see also chapter 8):

Thicker bark: A thicker bark protects the cambial layer, enabling trees to tolerate moderate-intensity fires[22]. Studies demonstrating the importance of this trait have been seen in three forest biomes. Examples of species with this trait include the Mediterranean cork oak (*Quercus suber*), larch (*Larix*) from Eurasian boreal forests, and the white pine *Pinus strobus* from temperate forests[23,24]. (See Box 4.)

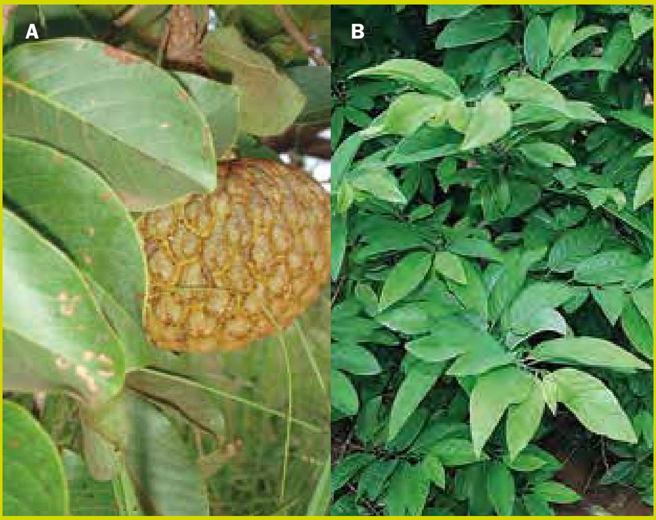
BOX 1: HIGHER WOOD DENSITY

Traits can vary in different individuals of the same species. For example, wood of fast-grown ash (*Fraxinus excelsior*) (**A**) is denser than wood of slow-grown individuals of the same species (**B**). This emphasises the importance of a traits-based approach to prediction of climate change effects, as different individuals of the same species may be more vulnerable than others.



BOX 2: LEAF THICKNESS

Species like *Annona crassiflora* (**A**) found in Brazilian savannas, are more able to tolerate drought due to their schlerophyllous leaves (hard, thicker, leathery)[15]. Other species in the same genera, such as *Annona squamosa* (**B**), may potentially be more vulnerable to drier conditions due to their thinner leaves.



BOX 3: DEEPER ROOTS

Species like *Dactylis glomerata* (**A**) are able to withstand drought due to their deeper roots. Species with shorter roots, such as *Trisetum flavescens* (**B**), are more vulnerable to drought[16].

THICKER LEAVES ARE BETTER ABLE TO WITHSTAND INCREASED TEMPERATURES

BOX 4: BARK THICKNESS

Species like Cork Oak (*Quercus suber)* (**A**) native to Mediterranean regions of southwest Europe and northwest Africa, are more resistant to fire due to thick bark[23]. Recent work indicates that thicker outer bark is more important in protecting the cambial layer than inner bark[40]. Other species, found at higher altitudes of these regions, like silver birch (*Betula pendula*) (**B**), may be less resistant to fires due to their thinner bark.

BOX 5: RESPROUTING ABILITY

Species like trembling aspen (*Populus tremuloides*) (**A**) in North Western Colorado, survive fires and other disturbances due to their ability to resprout after fires, wind storms and insect outbreaks[41]. This species may become more dominant in these forests over coniferous species like the lodgepole pine (*Pinus contorta*) (**B**), which cannot survive too frequent fires and are more vulnerable when disturbances are compounded[41].

Ability to resprout: After very intense fires, some species have the ability to regrow vegetatively to create new shoots and/or regenerate from dormant buds. This capacity to resprout allows species to quickly recover from fire events. Species displaying this trait have been found in three forest biomes and include, for example, the trembling aspen (*Populus tremuloides*) and the temperate *Sequoia sempervirens*[25–27]. (See Box 5 and also chapter 8.)

Presence of serotinous cones: These cones are fire-adapted and require burning to melt the resin covering the seeds, releasing them to be distributed by wind. Studies from several biomes have indicated that after fire, species with serotinous cones disperse a large amount of seeds that are able to germinate as soon as suitable temperature and moisture conditions are met, enabling them to quickly colonise new ground[28]. Examples of such species include the Californian *Pinus attenuata* and the jack pine, *Pinus banksiana*[25,29].

4. ELEVATED CO$_2$

Studies to examine traits that enable species to tolerate elevated CO$_2$ are few at present; most focus on how plant traits change as a result of elevated CO$_2$ (e.g. increase in biomass), and this varies according to the photosynthetic pathways used by the plants[24,30]. However, there are some general traits that are known to benefit species growing in higher CO$_2$. For example, a study in wet tropical savannas indicated that trees have an advantage over grasses because they can use the elevated atmospheric CO$_2$ levels to adjust their photosynthetic strategy, thus becoming more water-use efficient in drier conditions[31]. Other studies have proposed that increasing CO$_2$ will result in an improved water-use efficiency that may help plants to better tolerate other climate changes such as drought and warming[24,32], but this is an area where more work is required.

5. INCREASING FREQUENCY OF EXTREME CLIMATE EVENTS

There are relatively few studies currently available that look at traits that may enable species to tolerate increasing frequency of extreme climate events. A few studies have, however, been carried out on mangroves, where an increase in sea level rise and storms are expected, together with increased salinity. Experiments in Xiamen Island in Fujian Province, China, using seedlings of grey mangrove, *Avicennia marina*, show that higher growth rate and shoot-root ratio will enable plants to escape submergence of the canopy and may therefore be beneficial traits under future climate change[33]. Another study, in Myanmar, found that mangrove species that are able to resprout from nodes when damaged are better able to cope with storm events and increased sea level rise[34].

6. INCREASED NITROGEN DEPOSITION

Increasing temperatures in the tundra will promote thawing of the permafrost, which will release more plant-available nitrogen into the deeper zones of the soil profile. Studies in ombrotrophic peatlands in the Stordalen Nature Reserve in northernmost Sweden indicate that plants with deeper roots, such as knotberry (*Rubus chamaemorus*), are able to benefit more from this additional nitrogen availability than other species[35]. Another trait that enables species to benefit from this increased nitrogen concentration is greater leaf photosynthetic capacity, as has been shown for *Betula nana* in the Toolik Lake area, Alaska[36].

In summary, analysis to date suggests that the accelerating changes in the earth's climate will increasingly select for plants with certain traits. Plants with thicker leaves, more efficient water-use strategies, deeper roots, and higher wood density will probably be the 'winners'. Some traits are beneficial in response to multiple drivers, and plants with a combination of the traits described above appear to do particularly well[37–39]. In contrast, those without these traits will probably be less able to tolerate climate changes. This knowledge, combined with the evidence provided in chapter 11 of traits that make plants vulnerable to other environmental drivers in addition to climate change (e.g. land use change), highlights potential 'losers'. Plant species displaying these 'loser' traits, especially if already rare, endangered or economically important, should be the focus of current and future conservation and management strategies.

GLOBAL LAND-COVER CHANGE – WILDFIRES

How much of the Earth's terrestrial surface burns each year? Is the rate of burning increasing? Which vegetation biomes burn the most? Which plants are most flammable?

https://stateoftheworldsplants.com/2017/land-cover-change.html

EACH YEAR AROUND
340 MILLION
HECTARES OF THE EARTH'S
VEGETATED SURFACE BURNS

FIRE IS AN EMOTIVE TOPIC. EXTREME WILDFIRES CAN HAVE MASSIVE ECONOMIC, SOCIAL AND ENVIRONMENTAL IMPACTS[1], AND RECENT CATASTROPHIC FIRES, SUCH AS IN CANADA AND CHILE, DEMONSTRATE TO THE PUBLIC AT LARGE THE RAPID, DRAMATIC AND NEGATIVE IMPACTS OF FIRES[2].

But fire is also a naturally occurring global phenomenon that fundamentally affects many ecosystem patterns and processes, including the distribution and structure of vegetation[3]. Analyses of fires detected from satellite imagery during the last 16 years show that an average of around 340 million hectares of the Earth burns every year (Figure 1). Most of this burning is concentrated in biomes such as savannas, which experience orders of magnitude more fire than other biomes – around 10% of the savanna biome burns (Figure 2). This may seem unsustainable, but plants have evolved in conjunction with fire, and many plants have developed strategies that enable them to resist or even use fire to their own advantage[4]. So, while fires can threaten human life and cause extensive damage to crops and infrastructure, the impacts are heavily context-dependent and fire is a vital process in many ecosystems. Fire is not inherently bad. Rather, it needs to be considered within the context of a relevant fire regime.

FIRE REGIMES AND PLANT ADAPTATIONS

Fire regimes describe the unique disturbance patterns in an area as a function of: fire frequency (number of fires per unit time); fire interval (the time between fires); fire seasonality (the time of year fires occur); fire intensity (the energy output of the fire per unit time); fire severity (the impact of the fire on biota and ecosystems); and fire size (areal extent)[5,6]. Fire regimes differ around the world – fires in tropical and subtropical grasslands, savannas, and shrubland biomes of Australia and Africa burn frequently and over large areas, whereas the boreal forest biomes of Canada and Russia do not burn very often, but when they do are also capable of burning over large areas (Figure 2).

These fire-prone biomes often contain plants with specific adaptations that allow them to survive fires in three main ways: protection by thick, fast-growing bark[7,8]; resprouting from surviving tissues; and recruitment from seeds[9]. Thick bark as an adaptation to protect the living tissues in a plant stem from fire is found in numerous species, families and habitats. Notable examples include the cork oak (*Quercus suber*), the giant redwood (*Sequoiadendron giganteum*) and the ponderosa pine (*Pinus ponderosa*)[8]. In terms of resprouting, *Eucalyptus* species of Australia provide many good examples of epicormic resprouting (resprouting from buds on the trunk), which enables rapid recovery following fires (see Box 1), while plants from shrublands in Mediterranean climates, such as the strawberry tree (*Arbutus unedo*), may recover from a fire event by regrowth from swollen underground organs called lignotubers[10]. Other adaptations include a species' ability to recruit from seeds following fire. The lodgepole pine (*Pinus contorta*) in North America, for example, has serotinous cones that only open and release seeds after fires that are capable of melting the resin holding the pine cones shut[11], while the germination of seeds of *Boronia* species (Rutaceae) is enhanced by fire cues such as smoke and heat shock[12].

However, these fire-tolerant plants are adapted to particular fire regimes, rather than fire per se[13], so any change to the spatial and temporal pattern of fires can threaten their local survival. For instance, species such as lodgepole pine, whose adults are killed by fire and whose population persistence relies on seedling recruitment, are vulnerable when fires in an area become more frequent than the time required for them to reach maturity and produce seed. Similarly, species that rely on resprouting might be disadvantaged by an increase in fire intensity, as thin bark has only weak protection from the greater heat energy. Therefore, any change in fire regime may result in a change in species composition and even land cover. While there are no obvious patterns of changes in burning over the last 16 years at either the global (Figure 1) or biome (Figure 2) scales, analysis of the change in regime components of fire area (Figure 3b) and fire frequency (Figure 3c) demonstrate that there have been notable localised changes in fire regimes that will likely result in, or are the result of, land cover change.

Around 10% of

TROPICAL SAVANNA BIOMES

burn every year

FIGURE 1. GLOBAL TREND IN BURNED AREA, 2000–16

Burned area was taken from the MODIS era component of version four of the Global Fire Emissions Database[28].

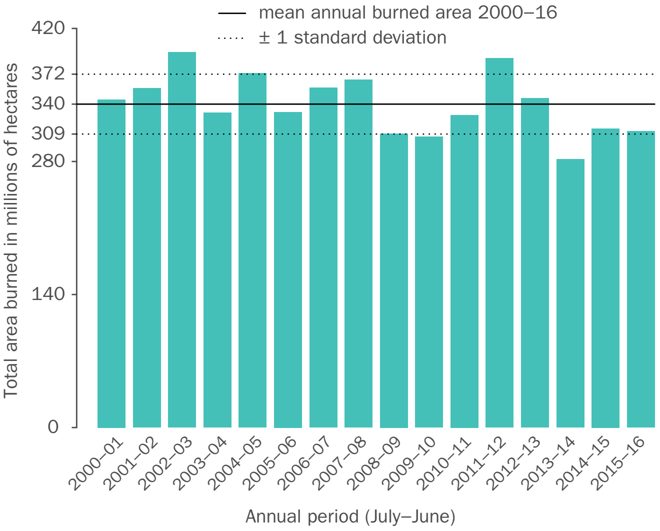
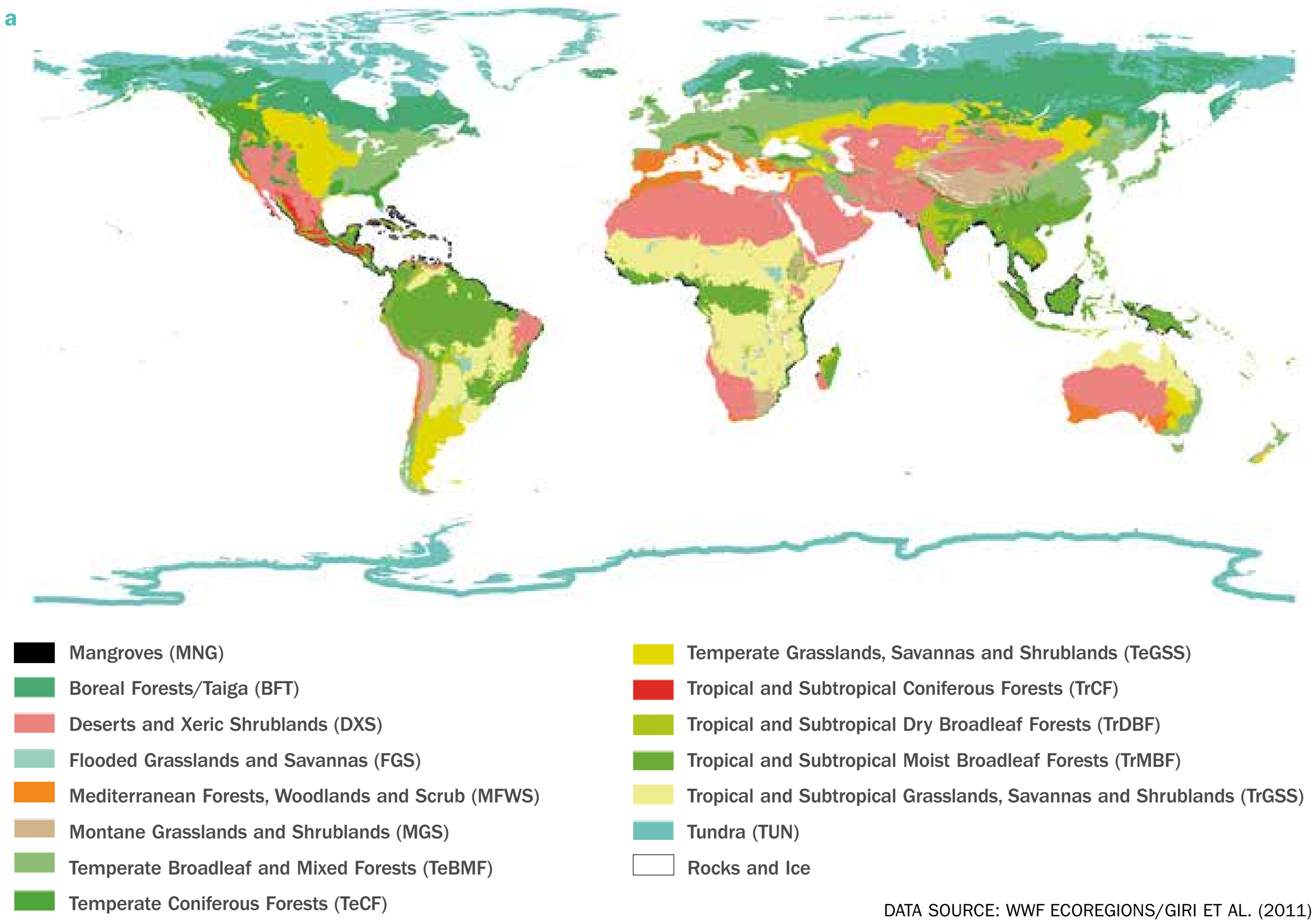
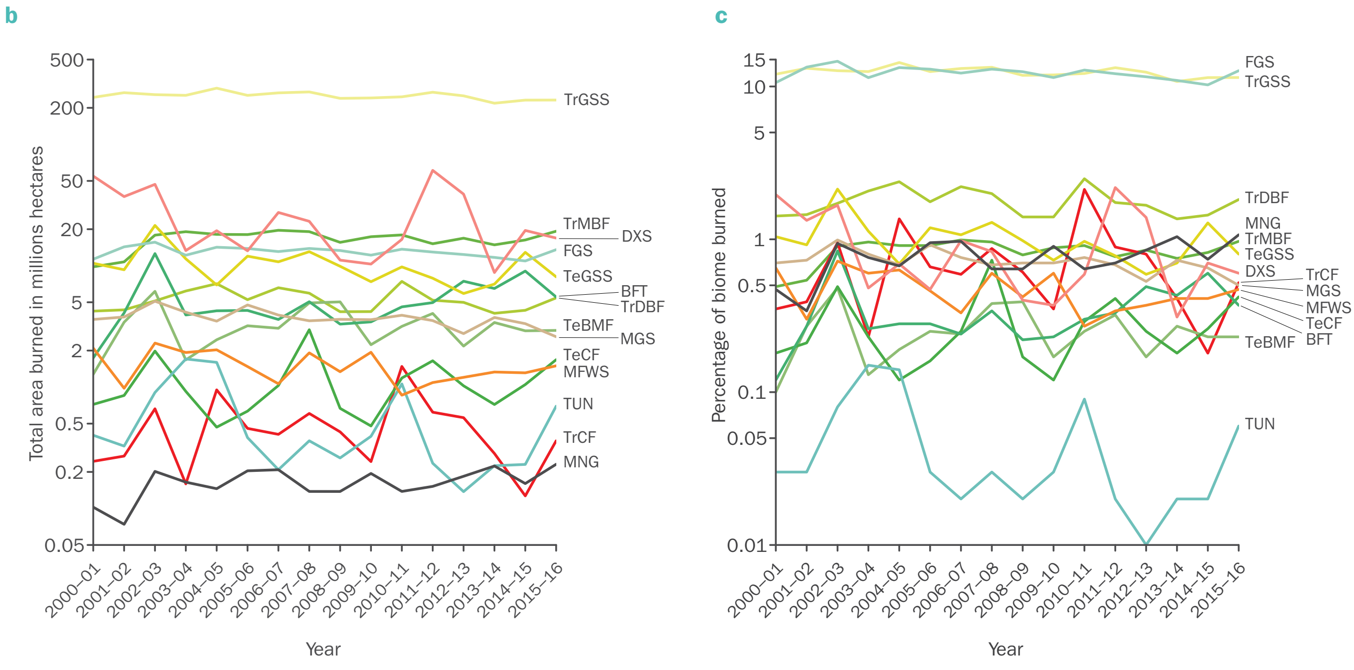


FIGURE 2: GLOBAL BURNING PATTERNS BY BIOME, 2000–2016

(a) The 14 biomes[29] that formed the basis of the analysis. Burned area was taken from the MODIS era component of version four of the Global Fire Emissions Database[28], to produce (b) total area burned in each biome each year, and (c) percentage area of each biome burned each year – please note the log y-axis scales.



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



PLANT FLAMMABILITY AND CHANGING FIRE REGIMES

There are three dominant factors that control fire regimes: atmospheric conditions, sources of ignition and resources to burn[14]. Analysis of climate data has shown that during the period 1979–2013, climatic conditions that promote fire, such as fire season length, became more common[15]. Patterns of fire ignitions will also be affected by climate change through an increase in lightning activity[16], though the main cause of increased ignition is human activity[17], as in Madagascar (see Box 2). Plants themselves are a determinant of the fire regime, as the flammability (i.e. the propensity to burn) of available fuel is a key driver of the spatial and temporal patterns of fire. Flammability is a complex plant trait consisting of multiple components, such as ease of ignition, the heat released when a plant or plant part burns, and the speed at which the fire spreads through the plant[4]. Such traits also vary considerably within a plant depending on which part of the plant is burned, and whether it is dead or alive. The plant flammability studies that have been conducted to date differ in terms of flammability components measured and the scale at which the measurements were made (i.e. from single leaves to entire plants and anything in between), depending on the particular questions that a study set out to answer. Without a consistent methodology we cannot yet combine the results of different studies to derive a global ranking of plant flammability. However, it is undeniable that some plant taxa are inherently more flammable than others, and we can make broad generalisations about which commonly studied plant families contain some of these most flammable species (see Box 3).

Given the differences in plant flammability, it should not be a surprise that when plant communities change, fire regimes will also change. For example, Chile has experienced a significant increase in fire frequency and intensity, including a series of fires early this year that burned on an unprecedented scale. These increases in fires have been attributed in part to monoculture plantations of *Pinus* and *Eucalyptus* forest. These plantations promote large fires not only by being highly flammable at the plant level, but also by occurring in continuous and homogenous blocks at the landscape level[18]. But perhaps the best examples of how changing plant communities can change flammability and fire regime is demonstrated by observing the effects of invasive species that act as unintentional field experiments. Invasive species can alter the inherent flammability and arrangement of fuel in a system and can therefore have substantial effects on fire regimes – for example through changes to fuel chemistry, the amount of live and dead material on plants and the amount and arrangement of fuel loads[19]. Indeed, weeds that alter fire regimes are among the most significant ecosystem-altering invasive plants. Such invasions commonly lead to increases in fire frequency and intensity, but may also modify ecosystem processes through suppression of fire activity. For example, invasions of highly flammable, pyrophillic (fire-loving) plants such as *Hakea* species (Proteaceae) and gorse (*Ulex europaeus*; Fabaceae)[20] into early successional New Zealand forests, are changing the flammability of the landscape and altering forest successions and hence land cover. Analogous patterns involving similar invaders have also been observed in ecosystems in Chile[21], and pines introduced for plantation forestry, such as the lodgepole pine in New Zealand and Patagonia, have become invasive and are altering fire regimes throughout the southern hemisphere[22]. Conversely, other invasive plants may cause fire-suppression feedback in fire-dependent ecosystems. For example, the fire-sensitive Brazilian pepper (*Schinus terebinthifolia*; Anacardiaceae) supresses fire where it invades fire-dependent pine savanna ecosystems in the US, which may drive a change in land cover from indigenous savanna to invasive-dominated forest[23].

BOX 1: EPICORMIC REGROWTH IN EUCALYPTS FOLLOWING A SEVERE FIRE AT GLENMAGGIE STATE FOREST, VICTORIA, AUSTRALIA

The first frame was taken in March 2013, within a month of the fire. The second frame was taken approximately one year after the fire and shows epicormic regrowth from *Eucalyptus muelleriana* (left and right foreground) and *E. polyanthemos* (right rear, silver foliage).

FIRE IS NOT INHERENTLY BAD AND IS A VITAL PROCESS IN MANY ECOSYSTEMS

FIRES IN MADAGASCAR BETWEEN JANUARY AND DECEMBER 2016

DATA SOURCE: VISIBLE INFRARED IMAGING RADIOMETER SUITE (VIIRS) SENSOR DATA

COPYRIGHT © http://viirsfire.geog.umd.edu/

BOX 2: FIRE IN MADAGASCAR

Pastoralists manage savannas in Madagascar for cattle grazing by periodic burning to promote the growth of grass, especially towards the end of the dry season each year. These fires can unintentionally invade forest edges, and frequent fires prevent forest succession and forest regeneration. Fires can also be used in shifting cultivation, in order to deliberately clear forest or establish land ownership. Since fire has traditionally been such a key part of land management and is closely linked with culture in rural areas, it is challenging for authorities to manage fire regimes. Recently, fire has also emerged as a means of political protest, with fires much more widespread during periods of political instability.

To better understand fire in Madagascar, we used time series data of daily observations from the AVHRR instrument between 1982 and 2015, and applied a contextual fire detection algorithm[44]. We then looked at the mean annual fire frequency (proportion of cloud-free looks in which active fire was detected) over this time period. Fires large enough to be detected did not occur in the moist tropical forests of the east coast. However, the savannas of the central highlands and the western dry forests are burned frequently, and the annual rate of burning has increased over the last 30 years. These patterns are similar to those for a single year (see map above for 2016).

MANAGING FIRE IN THE FUTURE

Understanding how changing fire regimes are likely to affect plants and hence global land cover is not easy, as there are multiple factors that interact in complex ways. For example, intuitively an increase in temperatures might be expected to increase fires, by creating hotter weather that is more conducive to fire. But where fire is limited by resources to burn, an increase in temperatures may actually reduce fires, as plant and hence fuel growth will decrease[14,24]. There have been very few studies to date that predict future fire activity in relation to biomes. But those that do indicate that in the shorter term we can expect fire to increase in drier biomes, and that in the longer term northern higher-latitude biomes, such as tundra and the boreal and temperate forests, will experience an increase in fire, while all tropical and subtropical biomes will experience a decrease (Figure 4). Such changes are not yet evident in our recent observations of burning by biome (Figure 2), but given the importance of climate to fire, it is inevitable that fire regimes will change in response to changing climate. In addition to changing climate, there are also examples of more abrupt changes to fire regime resulting from drivers such as extinction of megafauna, invasive species, collapse of rural lifestyles, and insect infestations[25].

Given fire regimes are changing, and extreme fire events are expected to increase[1], societies need to recognise the role that fire plays in ecosystem dynamics, and learn how to best manage changing fire regimes[2]. Fires can cause significant economic impacts, but there are also significant costs associated with firefighting, and in Canada these have been shown to have increased and become more variable during the period 1970–2013[26]. Therefore, rather than trying to exclude a natural ecosystem process, society instead needs to focus on managing the potential impacts. There are examples of how such planning can build resilient landscapes[27], but what is clear is that there needs to be an appreciation of the role plants can play in helping maintain or adapt existing fire regimes to manage future land cover change.

BOX 3: HIGH-LEVEL META-ANALYSIS OF PLANT FLAMMABILITY IDENTIFYING HIGHLY FLAMMABLE PLANT FAMILIES COMMONLY INCLUDED IN PLANT FLAMMABILITY STUDIES

SEARCH

Papers suggested by authors

Scopus search[a] (n =155)

Citation and reference checks for all relevant studies

SCREEN

Assess against criteria:

1. published ranks, or data that could be used to rank plants by their flammability
2. burnt fresh unprocessed plant material such as leaves or stems
3. included plants from at least 5 families

INCLUDE

Relevant flammability studies (n = 15)

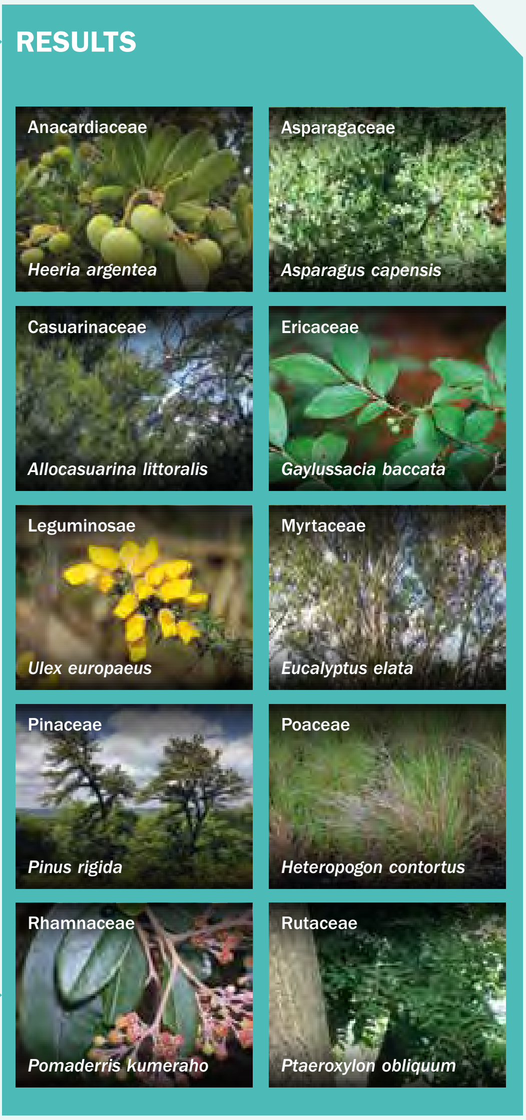
ANALYSIS

For each study create normalised family ranks using the most flammable species from each family (n=110)

For families occurring in >=3 studies (n=35), rank families based on minimum rank normalised values across all studies

Identify the 10 highest ranked families, and the family's most flammable species included in a study"

RESULTS



These species and families were selected from a high-level meta-analysis of 15 studies from around the world that measured flammability of live plant leaves and stems across 110 plant families[20,30–43].

[a] ((TITLE-ABS-KEY(rank*)) OR (TITLE-ABS-KEY(index))) AND ((TITLE-ABS-KEY(ignit*)) OR (TITLE-ABS-KEY(flammab*))) AND ((TITLE-ABS-KEY(plant*)) OR (TITLE-ABS-KEY(vegetation))) AND (LIMIT-TO(SUBJAREA, "ENVI") OR LIMIT-TO(SUBJAREA, "AGRI"))

FIGURE 3: GLOBAL FIRE REGIMES AND CHANGE, 2000–2016

The MODIS era component of version four of the Global Fire Emissions Database[28] was used to identify fire regime frequency as the number of months with burning, and fire regime area as the percentage area burned each year. (a) Fire regime map combining frequency and area components. (b) Change in fire area component, and (c) change in fire frequency component.

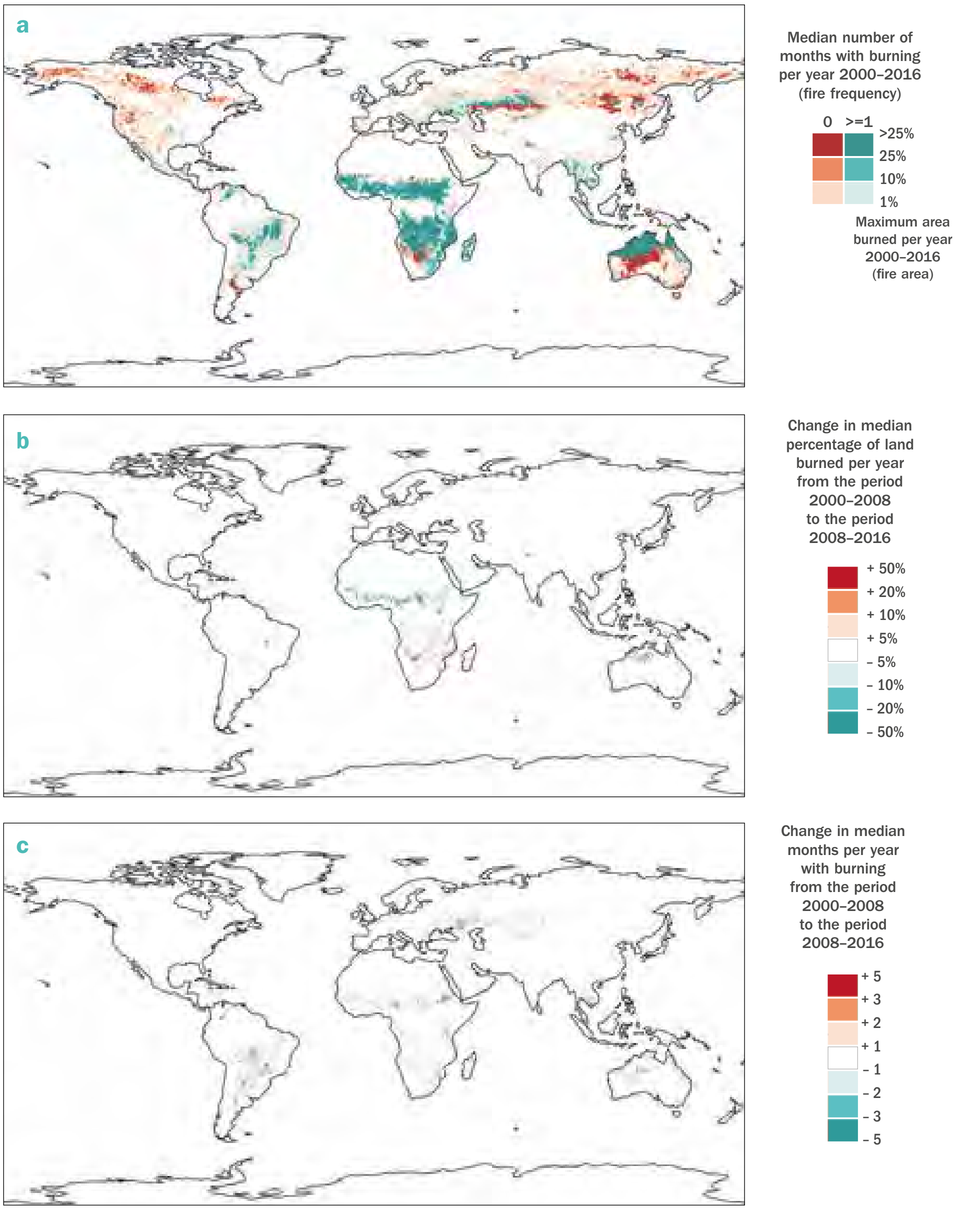
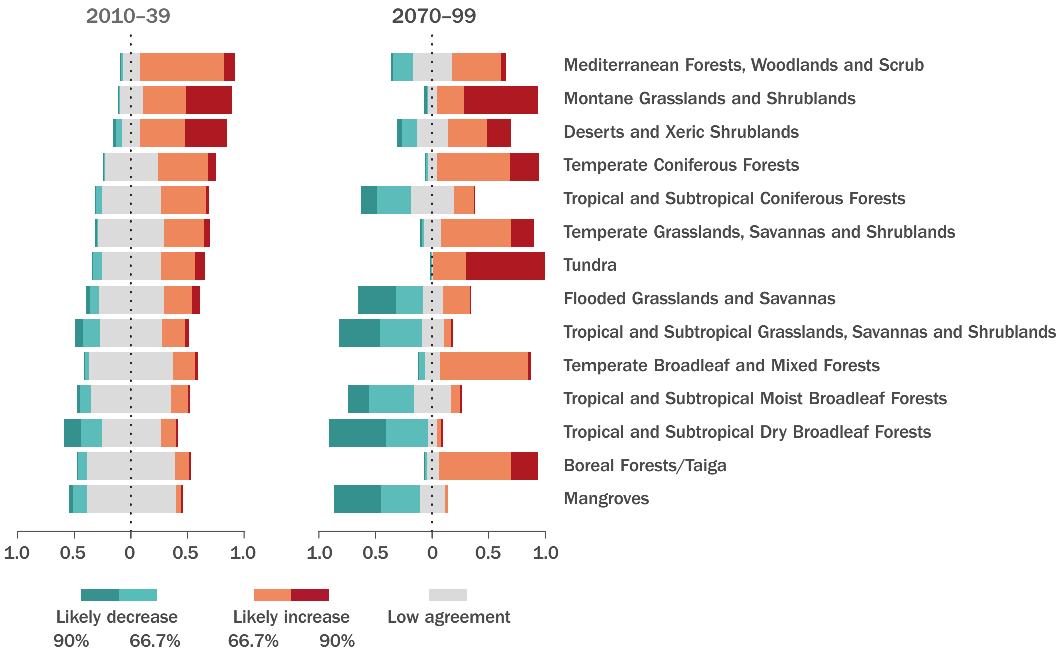


FIGURE 4: PREDICTIONS OF CHANGES IN FIRE ACTIVITY BY BIOME, USING THE BASELINE PERIOD 1971–2000

Likelihood of changes in fire activity are based on the agreement among 100-replicate ensemble models from 16 different climate predictions. Biomes are ordered by the proportion of lands in agreement for increased fire during 2010–39[14].



INVASIVE SPECIES

What are the most common methods used to control invasive plants? Which countries are carrying out most research on their control? Do different plant forms require different methods? What is the future for the control of invasive plants?

https://stateoftheworldsplants.com/2017/invasive-plants.html

6,075

SPECIES ARE NOW DOCUMENTED AS INVASIVE

INVASIVE SPECIES ARE AMONG THE MOST IMPORTANT DRIVERS OF BIODIVERSITY LOSS.

In last year's *State of the World's Plants,* we examined which plant families contained the highest number of alien invasive species, and the life forms of these plants. This year, we examine the different methods used to control invasive species, the most studied invasive families, life forms, and the countries undertaking invasive species research. We also discuss surprise effects that can sometimes occur when removing an invasive species from a landscape. We conclude with a brief overview of new technologies that are helping with early detection, monitoring, control and elimination of new plant invasions.

CONTROL OF INVASIVE PLANT SPECIES

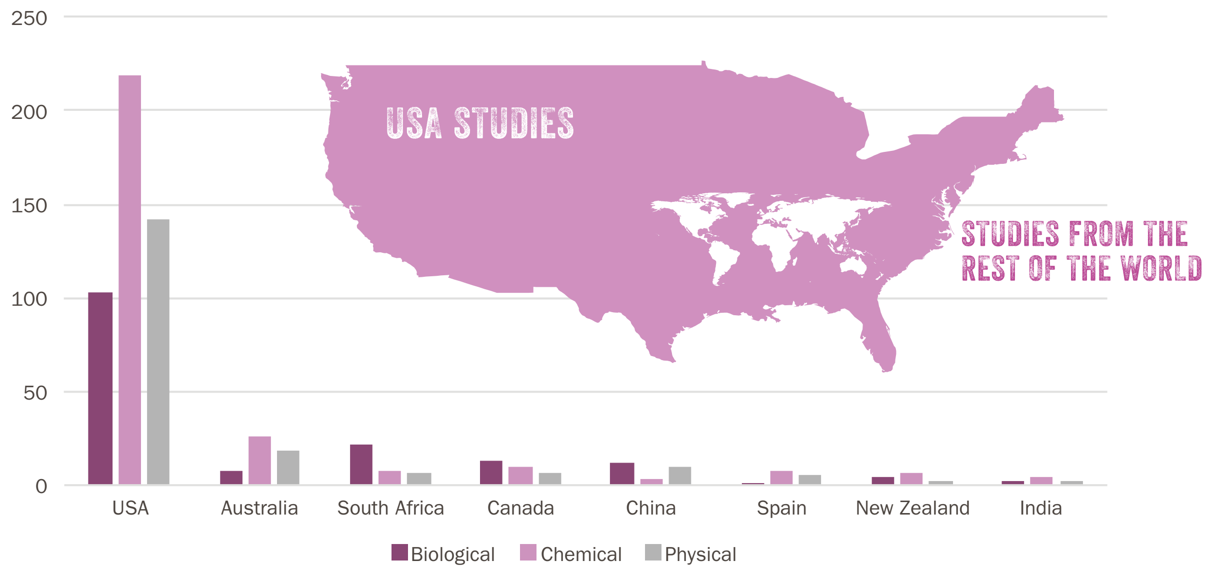
Along with biodiversity loss, invasive species can cause substantial environmental damage that impacts on important ecosystem services[1] (see Boxes 1 & 2). Determining methods to control invasive species is therefore an important global priority. Methods for controlling invasive plant species can be broadly classified into three categories: physical/mechanical, chemical or biological control[2]. Physical control involves manual removal of part or all of the plant (e.g. felling, cutting, ring-barking and hand-pulling); chemical control includes foliar spraying and treating cut stumps with herbicides; biological control involves the release of specially introduced natural enemies (e.g. fungal pathogens and insects) that reduce plant vigour or seed production[2,3]. Often, integrated control is necessary; this typically involves a combination of at least two of these methods. Physical and chemical control methods tend to be short-term activities suitable for smaller plant invasions that, with repeated follow-up, can result in complete eradication of the target species. In contrast, biological control is much more suited to large-scale invasions and aims to control (rather than eradicate) invasive plant species where other methods are impractical[2–4].

A systematic review of 771 studies published from 2007–16 on the control of invasive plant species in natural ecosystems, was constructed for this year's *State of the World's Plants*. This showed that the majority of research effort (83%) was directed at single control methods, with chemical control the most investigated (see Box 3). The three most invasive plant families (Compositae, Poaceae and Fabaceae) accounted for more than a third of the studies (Table 1), and the greatest concentration of these studies involved invasive plants in the US, followed by Australia (Figure 1).

The choice of method for controlling invasive species shows some interesting differences according to plant life form. Physical and chemical methods are most commonly used to control herbaceous plants including hemicryptophytes (biennial and perennial herbs), therophytes (annuals) and cryptophytes (possessing an underground storage organ). In contrast, biological control is mainly used to control hemicryptophytes, phanerophytes (woody trees) and nanophanerophytes (woody shrubs).

Evaluation of the effectiveness of different control methods is vital for management and performance and should be assessed at both a population level and a programme level[5]. Key to successful evaluation is collecting the right data, and standard protocols are available which can be customised for individual cases. With these data, performance goals can be evaluated and, if necessary, decisions made to change the course of management[5]. It may be that for the worst invasives control is not possible and we need to adopt a different paradigm. For example, in a review of the effectiveness of controlling lantana (*Lantana camara*) across South Africa, India and Australia, Bhagwat et al.[6] highlighted a complete lack of success and suggested the need to adopt adaptive management rather than fighting a losing battle.

FIGURE 1: TOP EIGHT COUNTRIES IN WHICH PHYSICAL, CHEMICAL AND BIOLOGICAL CONTROL ON INVASIVE PLANT SPECIES IN NATURAL ECOSYSTEMS ARE BEING STUDIED, AND THE NUMBER OF PUBLISHED STUDIES PER COUNTRY



BOX 1: *LEUCAENA LEUCOCEPHALA* – MIRACLE TREE OR DETRIMENTAL INVADER?

Leucaena leucocephala was hailed a miracle tree at the height of its popularity in the late 1970s and early 1980s because of its fast growth and ease of propagation and management[24]. Its multiple uses include firewood, biofuel, poles, paper production, livestock fodder, green manure, food, shade, reforestation, as a windbreak and soil stabiliser, and as a soil improver due to its nitrogen fixation ability[e.g. 24–28]. Yet this miracle tree is listed in '100 of the World's Worst Invasive Alien Species'[28] and is considered a weed in over 25 countries (including Madagascar) and across all continents except Antarctica[25,29]. The extensive list of published studies on *L. leucocephala* productivity, digestibility, genetic diversity and resistance against pests and diseases[30], stands in stark contrast to the increasing research effort on impacts, spread and control of this species[e.g.31–33]. Recent research effort has examined the merits of seedless new hybrids, which would limit the species' ability to spread[34]. Yet there is the possibility that hybrids could cross with fertile congenerics, exacerbating the problem of this invasive genus[35,36]. Invasiveness has already been documented as varying at the subspecies level: subspecies *leucocephala* is considered weedy while subspecies *glabrata* is not, most likely due to the much more recent introduction of *L. leucocephala* subsp. *glabrata*[25]. The ultimate question is: do the potential benefits outweigh the likely risks?

BOX 2: THE WORKING FOR WATER PROGRAMME IN SOUTH AFRICA

Some of the worst introduced invaders in South Africa are trees, including *Acacia*, *Pinus* and *Eucalyptus* species, which were introduced as tannin or timber sources[37]. Observations of reduced streamflow due to increased evapotranspiration following afforestation[38,39] have led to concerns over the impacts of these species, particularly along riparian zones, in water catchments and in drought-prone regions[37]. In addition to reducing water availability and displacing native vegetation, these trees change ecosystem functioning by altering the pH and nutrient status of the soil[37]. Furthermore, pines contain flammable resins, which has led to more intense fires and increased soil erosion in fire-prone ecosystems like the fynbos[3,40]. The Working for Water programme was initiated in 1995, to target removal of woody plant species invading catchments, with the goal of increasing water supply[41].

An equally important aim of this programme was to create employment, resulting in alleviation of poverty in some of the poorest communities[42]. The wood resource generated by removal of the invasive species is used by local communities and has reduced fire severity in the bush[41]. Although there is public support for the overall programme, there has been strong opposition to tree removal in the Table Mountain National Park on recreational and aesthetic grounds[43]. Difficulties have also arisen from unsuccessful attempts to effectively combine ecological, economic and social goals[41]. Improved management, with effort concentrated on priority areas and species, is essential for the success of this ambitious programme[44].

44% OF STUDIES ON CONTROL OF INVASIVE PLANTS IN NATURAL ECOSYSTEMS EXAMINE THE USE OF CHEMICAL METHODS

TABLE 1: THE TOP TEN INVASIVE FAMILIES IN TERMS OF NUMBERS OF PLANT SPECIES THAT WERE THE SUBJECT OF STUDIES OF CONTROL METHODS IN NATURAL ECOSYSTEMS

PLANT FAMILY (N = 226)	COMMON NAME	NUMBER OF SPECIES (N = 6,075)	NUMBER OF CONTROL METHODS (N = 771)
Compositae	Daisy family	650	90
Poaceae	Grass family	649	146
Fabaceae	Legume family	477	40
Rosaceae	Rose family	290	7
Brassicaceae	Mustard family	219	16
Lamiaceae	Mint family	173	3
Amaranthaceae	Amaranth family	163	5
Caryophyllaceae	Pink family	139	12
Cyperaceae	Sedge family	131	4
Plantaginaceae	Plantain family	124	7

* The inclusion of a further two new global databases[45,46] to the original four[47–51] described in State of the World’s Plants 2016[52], has raised the number of documented invasive alien vascular plant species in global lists from 4,979 to 6,075 species.

CONSEQUENCES OF INVASIVE SPECIES REMOVAL

Invasive species removal can result in the unexpected proliferation of another invasive species, termed a ‘surprise effect’[7]. Surprise effects in plants can result from the removal of another invasive plant species, known as competitive release, or an invasive herbivore species, termed top-down release[8]. Competitive release has been observed in the increase of lantana (*Lantana camara*) following the removal of invasive red sesbania (*Sesbania punicea*) in South Africa, and in the spread of invasive alligator weed (*Alternanthera philoxeroides*) with the removal of water hyacinth (*Eichhornia crassipes*) from Lake Seminole in Florida[9]. Top-down release is seen in the proliferation of turpeth (*Operculina ventricosa*; accepted name *O. turpethum* var. *ventricosa*), following feral goat and pig eradication on the Pacific island of Sarigan[10].

Consideration of possible interactions between invasive and potentially invasive species is vital before eradication efforts commence, to ensure the likelihood of surprise effects are minimised[7,11]. A solution to this is to adopt an ecosystem-level approach, with control management initiatives targeting several species simultaneously[11]. A multiple eradication programme of early-stage plant invaders in the Galapagos has shown that continued control and monitoring for a sufficient period of time is also crucial to success[11–13].

THE FUTURE FOR CONTROL OF INVASIVE SPECIES

New technologies are playing an increasingly important role in our efforts to detect, monitor, control and eradicate invasive plant species. Remote sensing mapping using Landsat imagery and drones is being used to improve early detection, map distribution and spread, and to monitor the efficacy of control and eradication activities[14–17].

Rapid advances in molecular biology, such as RNA-guided gene drives, has also brought the theoretical possibility of introducing genes into invasive species to enable targeted population suppression much closer to reality[18]. However, as with the use of genetically modified crops, this will be open to controversy and concerns over safety and will require independent scientific assessment of possible impacts and public engagement prior to their use[18].

Smartphone technology is another area where new technologies are enabling citizen scientists and plant enthusiasts to submit information about invasive plant species in Britain[19] and Europe[20]. Public participation in the detection of invasive species in this way is greatly increasing the ability of researchers to collect data across much wider spatial and temporal scales[21,22]. The invasive plant app *PlantTracker*, for example, has received 20,353 records plus 19,241 photos of the 22 worst plant invasives in the UK since it launched in 2008[23]. Volunteers have been successfully trained to identify invasive plants by video as well as in person[5,22].

Engaging citizens through the use of new technologies in this way not only enables the rapid detection of potentially invasive species, vastly improving the ability to monitor, control and eradicate new invasions, but also raises the awareness of invasive plant species issues in the public domain[21] and possibly represents one of the best long-term controls against invasive species.

BOX 3: THE TOP TEN HERBICIDES USED IN CHEMICAL CONTROL STUDIES OF INVASIVE PLANT SPECIES IN NATURAL ECOSYSTEMS

HERBICIDE NAME	NUMBER OF STUDIES	SELECTIVE	MODE OF ACTION
1 Glyphosate	149	N	Amino acid synthesis inhibitor
2 Triclopyr	57	Y (broadleaf)	Synthetic auxin, growth disruption
3 Imazapyr	50	N	Amino acid synthesis inhibitor
4 Imazapic	43	Y (broadleaf, some grasses)	Enzyme synthesis inhibitor
5 Metasulfuron-methyl	32	Y (broadleaf, some grasses)	Enzyme synthesis inhibitor
6 2, 4-D amine	30	Y (broadleaf)	Synthetic auxin, growth disruption
7 Aminopyralid	24	Y (broadleaf)	Synthetic auxin, growth disruption
8 Picloram	23	Y (broadleaf)	Synthetic auxin, growth disruption
9 Clopyralid	14	Y (broadleaf)	Synthetic auxin, growth disruption
10 Fluroxypyr	13	Y (broadleaf)	Synthetic auxin, growth disruption

The most frequently used herbicide currently reported as being used to control invasive plants is the non-selective glyphosate. Eight of the other top ten herbicides are selective – six of these target broadleaf plants and two control both broadleaf plants and some grasses.

Selective herbicides have the benefit of not harming some non-target plants[53]. Of concern is the development of herbicide resistance, which occurs as a result of repeated and intense use in agriculture and the fact that the majority of these herbicides share similar mechanisms to control plants[53,54].

PLANT HEALTH – STATE OF RESEARCH

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

https://stateoftheworldsplants.com/2017/plant-health.html

POTENTIAL COSTS OF

US$540 BILLION PER YEAR

TO WORLD AGRICULTURE IF SPREAD OF INVASIVE PESTS AND PATHOGENS IS NOT STOPPED

INTRODUCED INSECTS AND DISEASES HAVE EFFECTIVELY ELIMINATED ENTIRE TREE SPECIES FROM UNITED STATES FORESTS WITHIN DECADES[1].

In 2016, an analysis of 1,300 known invasive pests and pathogens estimated their potential cost to global agriculture at over US$540 billion per year if they continue to spread[2]. China and the US represent the richest potential sources for new invasions to other countries, given the invasive species they already contain and their volume of trade[2]. As the world's largest agricultural producers, the US and China also face the greatest costs from further invasions. However, relative to GDP the greatest costs are faced by developing countries[2]. In a world in which species invasions show no signs of approaching saturation, international cooperation is needed to reduce the further spread of invasive pests and pathogens[3].

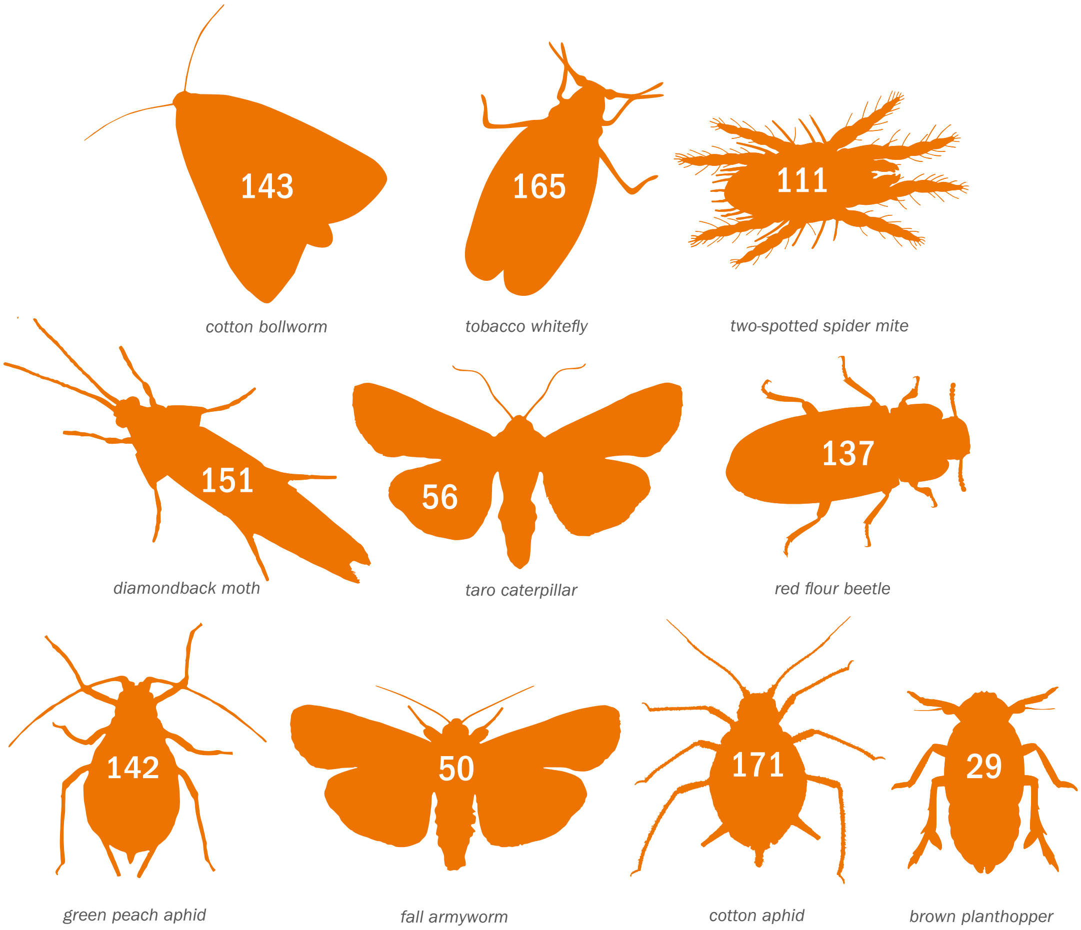
These potential future costs are on top of the present cost of plant pests and pathogens. In the European Union alone, 196,000 tonnes of pesticides are used each year against fungi, bacteria, arthropods and molluscs[4]. Pests and pathogens have killed billions of trees in forest and urban settings worldwide over the last two decades.

In last year's *State of the World's Plants,* we focused on viral, fungal and bacterial pathogens; this year, we focus on insect pests of plants. Not only do phytophagous insects damage plants but they may also act as significant vectors of many viral, fungal and bacterial pathogens. Of the top ten viruses identified in last year's report, eight are transmitted by insects including aphids, whiteflies and thrips. For example, *Xylella fastidiosa*, a bacterial pathogen spreading across Europe and devastating olive production in the Mediterranean, is transmitted by species of leafhopper[5].

RESEARCH EFFORT ON INSECT PESTS

The Centre for Agriculture and Biosciences International (CABI) keeps track of pests and pathogens around the world. It currently publishes full datasheets for 1,187 arthropod pests in its Compendia[6] on Crop Protection (1,153 arthropods), Forestry (484 arthropods) and Invasives (339 arthropods). The top 20 insect pests in terms of scientific publications in CABI abstracts in the last five years are shown in Table 1. These pests are geographically widely distributed (Figure 1), have a large host range, are still spreading and are resistant to many pesticides.

FIGURE 1: TOP 10 ARTHROPOD PESTS (SEE TABLE 1) AND THE NUMBERS OF COUNTRIES THEY ARE CURRENTLY PRESENT IN



[a] Countries where the pest is described as 'widespread', 'present' or 'restricted distribution' according to the CABI datasheet. Sub-country regions were summarised to the country level.

TABLE 1: TOP 20 PESTS BY RECENT PUBLICATION NUMBERS

Ranking is based on abstract searches on all 1,187 arthropod pests with full datasheets in the CABI Compendia on crop protection, forestry and invasive species. Also included are the number of pesticide active ingredients to which they are reported to be resistant, and summaries of their reported distribution and reported hosts.

SCIENTIFIC NAME	COMMON NAME	NUMBER OF PUBLICATIONS (2012–16)	NUMBER OF PESTICIDES RESISTANT TO	CONTINENTS PRESENT[A]	NUMBER OF HOST GENERA[B]	TOP HOSTS (BY PUBLICATION NUMBER)[C]*
Helicoverpa armigera	cotton bollworm	1,619	49	Asia, Africa, South America, Europe, Oceania	50	*Gossypium* (cotton), *Cicer arietinum* (chickpea)
Bemisia tabaci	tobacco whitefly	1,528	56	Asia, Africa, N/S America, Europe (few occurrences), Oceania	36	*Solanum lycopersicum* (tomato), *Gossypium* (cotton)
Tetranychus urticae	two-spotted spider mite	962	95	Asia, Africa, N/S America, Europe, Oceania	80	*Solanum lycopersicum* (tomato), *Phaseolus vulgaris* (common bean)
Plutella xylostella	diamondback moth	926	95	Asia, Africa, N/S America, Europe, Oceania	15	*Brassica oleracea* (cabbage), *Brassica*
Spodoptera litura	taro caterpillar	853	39	Asia, Africa, N America, Europe, Oceania	66	*Glycine max* (soybean), *Arachis hypogaea* (peanut)
Tribolium castaneum	red flour beetle	829	33	Asia, Africa, N/S America, Europe, Oceania	39	*Triticum* (wheat)
Myzus persicae	green peach aphid	811	80	Asia, Africa, N/S America, Europe, Oceania	95	*Solanum tuberosum* (potato), *Capsicum annuum* (bell pepper)
Spodoptera frugiperda	fall armyworm	668	24	Africa, N/S America, Europe (few occurrences)	72	*Zea mays* (maize), *Gossypium* (cotton)
Aphis gossypii	cotton aphid	610	46	Asia, Africa, N/S America, Europe, Oceania	65	*Gossypium* (cotton)
Nilaparvata lugens	brown planthopper	603	31	Asia, Oceania	2	*Oryza* (rice)
Spodoptera exigua	beet armyworm	506	39	Asia, Africa, N America, Europe, Oceania	50	*Gossypium* (cotton), *Zea mays* (maize)
Frankliniella occidentalis	western flower thrips	465	30	Asia, Africa, N/S America, Europe, Oceania	64	*Solanum lycopersicum* (tomato), *Capsicum annuum* (bell pepper)
Ceratitis capitata	Mediterranean fruit fly	437	3	Asia, Africa, N/S America, Europe, Oceania	107	*Citrus* (citrus)
Cydia pomonella	codling moth	421	22	Asia, Africa, N/S America, Europe, Oceania	6	*Malus* (apple)
Callosobruchus maculatus	cowpea weevil	409	2	Asia, Africa, N/S America, Europe, Oceania	13	*Vigna unguiculata* (cowpea), *Vigna radiata* (mung bean). Mainly affects stored products.
Spodoptera littoralis	cotton leafworm	401	30	Asia, Africa, Europe	96	*Gossypium* (cotton), *Zea mays* (maize)
Acyrthosiphon pisum	pea aphid	392	Not in database	Asia, Africa, N/S America, Europe, Oceania	34	*Medicago sativa* (alfalfa), *Pisum sativum* (pea)
Diaphorina citri	Asian citrus psyllid	385	7	Asia, Africa, N/S America, Oceania	2	*Citrus* (citrus)
Tuta absoluta	tomato leafminer	375	14	Asia, Africa, N/S America, Europe	11	*Solanum lycopersicum* (tomato), *Solanum tuberosum* (potato)
Thrips tabaci	onion thrips	362	19	Asia, Africa, N/S America, Europe, Oceania	28	*Allium* (onion)

[a] Continents with at least one country where the pest is 'widespread', 'present' or 'restricted distribution'. N. America includes Central America.

[b] Hosts, as reported on the CABI datasheet, summarised to the generic level.

[c] Top hosts by publication number overall: 1. *Solanum lycopersicum* (tomato), 2. *Gossypium* (cotton), 3. *Oryza sativa* (rice), 4. *Zea mays* (maize), 5. *Citrus*, 6. *Capsicum annuum* (bell pepper), 7. *Brassica oleracea* var. *capitata* (cabbage), 8. *Malus domestica* (apple), 9. *Oryza* spp., 10. *Glycine max* (soybean).

Top of this list is the cotton bollworm (*Helicoverpa armigera*). This is a major pest of cotton (*Gossypium* spp.), maize (*Zea mays*), pulses (Fabaceae), tomatoes (*Solanum lycopersicum*) and sorghum (*Sorghum bicolor*) throughout most of the world, but has only recently arrived in the Americas where it is still spreading. It has documented resistance to 49 pesticides. The tobacco whitefly (*Bemisia tabaci* complex) is a widespread pest of field crops throughout the tropics and subtropics, and can transmit over 100 viruses. Different sibling species of tobacco whitefly have independently spread throughout the world, including into temperate regions where they are particularly damaging in glasshouses.

To gain insights into which insect pests may have been of increasing concern over the past decade, we also examined the top 10 pests on which established research programmes have intensified over the past 10 years (Table 2). It is led by the spotted wing drosophila (*Drosophila suzukii*), a fly from East Asia that infests rosid fruit; first found in North America in 2008, it has now been found in Europe. Next is the brown marmorated stink bug (*Halyomorpha halys*), which was accidentally introduced into the US in the late 1990s a nd Europe in 2008[7] and affects a wide range of host crops.

It is notable that sub-Saharan African countries harbour relatively few of the pests on which most research is done. The false codling moth (*Thaumatotibia leucotreta*), which is endemic to sub-Saharan Africa, has only recently seen an intensification of research effort, but this is driven by the biosecurity requirements to prevent it spreading out of Africa, rather than its direct impact on agricultural production in Africa. As with viral, fungal and bacterial pathogens, research effort is heavily biased towards the highest producing countries and those with more readily available access to research funding. This highlights the limitations of using research effort as a metric to indicate the significance of global plant health threats.

CAUSES OF GLOBAL INCREASES IN PLANT INSECT PESTS

Growth in international trade and travel has been implicated in the spread of insect pests over the globe[1,8–12]. Reduced control of movement of plants within the European Union single market has contributed to recent increases in the rate of spread of insect pests within this region[8,9]. Importation of plants-for-planting is recognised as the highest risk pathway for entry of insects. Nursery stock was the most common route for entry of alien pests and pathogens of forestry into the US during the period 1860– 2006[10]. Untreated wood packaging is also a common entry pathway[1] and the source of a recent outbreak of the Asian longhorn beetle in the UK[11]. A recent study highlights eight wood borers found in North America that could gain entry to Europe by trade in woodchips[12], placing European forests at risk.

Not all outbreaks of insect pests are due to alien invasions. Outbreaks of pests can also occur periodically due to weather patterns and other factors. For example, shifts from solitary to gregarious forms of the desert locust (*Schistocerca gregaria*) in response to population increase is likely driven by changing patterns of resource distribution[13], giving rise to devastating, dispersing swarms that ravage crops.

In recent years, climate change may have contributed to some outbreaks, through latitudinal range shifts of pest species[14,15]. For example, one study showed that northern expansion of the pine processionary moth (*Thaumetopoea pityocampa*) in France in the early 2000s coincided with an increase in favourable larval feeding conditions as predicted from climate data[16]. However, clearly distinguishing the effects of climate change from the effects of pest evolution and changes in insect behaviour (behavioural plasticity) can be difficult. For example, climate change has been cited as a cause of worldwide expansion of the Colorado potato beetle, but this is hard to disentangle conclusively from other factors[14].

Increasing numbers of arthropod species have evolved resistance to pesticides, and many of the top 20 pests are now resistant to a large number of pesticides (Table 1). The withdrawal of some insecticidal active ingredients, due to environmental and public health concerns, has further limited scope for rotating pesticide actives and increased selection for pesticide resistant biotypes. The discovery of new pesticide active ingredients is recognised as a major challenge. Yet the cost of bringing a new pesticide active ingredient from discovery through to registration has risen sharply, partly due to increased regulation and research costs: since 2005–08, costs have risen by US$30 million to $286 million for the period 2010–14, a rise of 11.7%[17]. This will mean fewer insecticide-based options to control current and future outbreaks of pests.

ECONOMIC IMPACTS

It is impossible to make precise assessments of the economic impact of insect pests (both invasive and non-invasive) of plants globally. The annual global spend on insecticides is over US$15 billion. Although monetary values can be assigned to commercial crops, they are not easily compared with damage to natural capital. Economically important crops and large agricultural economies will tend to dominate the numbers and mask devastating impacts on more local levels or specialised crops. Despite this, attempts are being made at valuing non-commercial plants (e.g. in terms of ecosystem services) and assessing their need for pest management[18].

The emerald ash borer (*Agrilus planipennis*) could cost the USA over $300bn (see Box 1). In the US, the cost of invasive forest pests is carried disproportionately by local rather than national government even when national government-funded eradication programmes exist (Figure 2), due to the costs of safe removal of dangerous trees[20].

Insect pests also cause considerable costs to ecosystem services[18]. A recent paper modelling the carbon storage and nitrogen leaching consequences of pest-induced tree species change in north-eastern US forests[21], indicated that destruction of hemlock by the hemlock woolly adelgid (*Adelges tsugae*) and natural replacement by yellow birch, could result in short-term losses to the carbon pool and

TABLE 2. TOP TEN PESTS FOR RESEARCH INTENSIFICATION.

Measured by shift in publication number ranking from 2007–11 to 2012–16.

SCIENTIFIC NAME	COMMON NAME	NUMBER OF PUBLICATIONS (2007– 11)	NUMBER OF PUBLICATIONS (2012– 16)	RANK INCREASE	EXAMPLE HOST PLANTS	TRIGGERS OF INTENSIFICATION
Drosophila suzukii	spotted wing drosophila	33	315	118	Rosid fruits	Invasion of US and Europe from 2008 onward.
Halyomorpha halys	brown marmorated stink bug	36	155	76	Rosid fruits	Accidental introduction into US and spread across majority of US states. Serious crop losses since 2010. Spread to Europe in 2008.
Bactericera cockerelli	tomato/ potato psyllid	78	185	53	Solanaceous plants	Native species of US, recently causing extensive economic losses. Invasion of New Zealand in 2000s, with potential to move to Australia.
Tuta absoluta	tomato leafminer	156	375	49	Solanaceous plants	Spread from South America, through Europe in the late 2000s, to Middle East and Africa.
Thaumatotibia leucotreta	false codling moth	24	62	37	*Citrus* (citrus), *Gossypium* (cotton), *Zea mays* (maize)	Biosecurity to prevent spread out of Africa.
Sogatella furcifera	white-backed planthopper	122	214	34	*Oryza sativa* (rice)	Increased resistance to pesticides and plant defences in East and South-East Asia.
Diaphorina citri	Asian citrus psyllid	204	385	33	*Citrus* (citrus)	Spread from Asia to Middle East and America. Attempts to contain spread in US.
Conogethes punctiferalis	castor capsule borer	29	62	32	Polyphagous	Widespread in South and East Asia, efforts to prevent spread to rest of world.
Paracoccus marginatus	papaya mealybug	41	76	31	*Carica papaya* (papaya), *Manihot esculenta* (cassava), *Hibiscus*, *Annona*	Invasion of Africa and South and South-East Asia from America; attempts at biological control.
Cydalima perspectalis	box tree moth	21	48	29	*Buxus* (box), *Ilex chinensis* (Kashi holly), *Euonymus japonicus* (Japanese spindle plant), *Euonymus alatus* (burning bush)	Invasion of Europe from Asia.

long-term increases in nitrate leaching[21]. Another study on the effects of the mountain pine beetle (*Dendroctonus ponderosae*) in British Columbia suggests that its impact on carbon sequestration could be as great as four years' worth of Canada's carbon dioxide emissions[22].

However, not all insects are bad news for plants – some insects make major contributions to pollination of crops, natural predation and soil health[23]. It has been estimated that the economic value of natural control of insect pests by other insects is worth around $4.5 billion annually to agriculture in the US[24]. There are at least 78 insects listed as biological control agents by the European and Mediterranean Plant Protection Organization.

CONTROL OF INSECT PESTS OF PLANTS

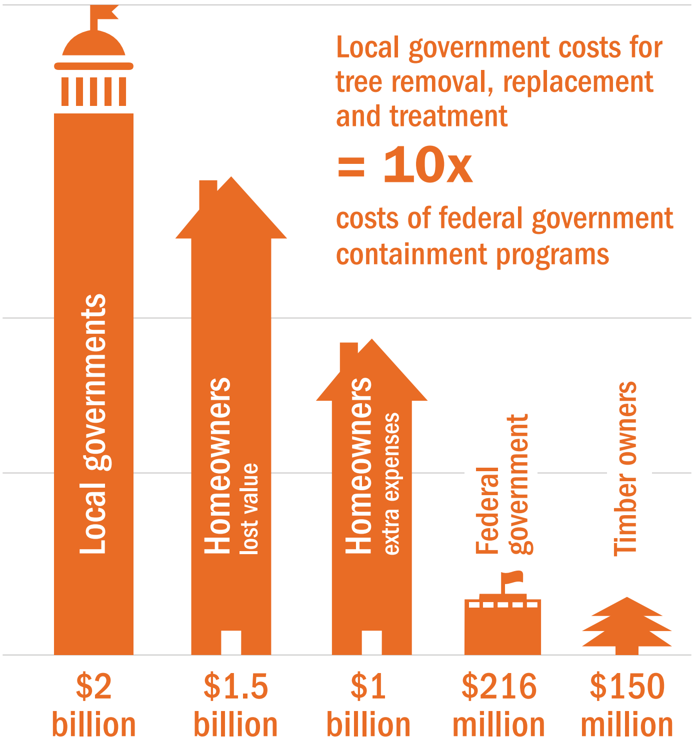
There is clearly a huge global imperative to control insect pests of plants. The costs of controlling the spread of invasive pests will in many cases be lower than the cost of the damage caused by an invasion. Control of regulated or quarantine pests typically occurs in the following order: (1) prevention of entry to a country or area, (2) eradication and containment, and (3) management using tools such as biological control, pesticides and biopesticides, plant resistance, cultural methods, and natural enemy encouragement.

Biosecurity: Strengthening of plant biosecurity at international borders has been recommended repeatedly by many epidemiologists[25–29] and is at the core of the International Plant Protection Convention (IPPC), to which 182 Parties are signatories. However, effective biosecurity can vary significantly between countries as it is dependent on their geography, climate, established trading relationships and availability of resources. Increasingly, countries are seeing the value of collective action and are recognising that biosecurity must be seen as a continuum spanning pre-border, border and post-border activities[30]. Increased pre-border security measures and surveillance activities are needed to give advance warning of potential pests and potential pathways of introduction[31]. Post-border surveillance is also needed to allow early identification of outbreaks, and for eradication and containment measures to be implemented.

Eradication and containment: A review published in 2016, found that eradication campaigns for insect pests are increasingly used and are often successful[32]. Maximising the chances of success of eradication relies on advance knowledge of new threats and on rapid identification of new outbreaks. Knowledge of the pest and its hosts is needed to develop effective early detection methods and design a rapid eradication plan with financial resources and materials immediately available to implement it[33]. Confirmation of effective eradication can be lengthy and expensive. In one recent example from New Zealand[34], a range of measures were used to control the great white butterfly (*Pieris brassicae*), which was attacking brassicas and native cresses. Since the last finding in 2014, it has required over 100,000 surveillance inspections at 29,445 locations, over a period of time equivalent to six generations, to confirm that the eradication measures were successful. Citizen science also played a role alongside traditional surveillance, with the general public encouraged to report potential sightings. Containment of a pest is sometimes attempted instead of eradication. In the European Union, 'Protected zones' can be designated for specific pests, with increased phytosanitory measures to maintain their pest-free status. Even if containment measures fail, they can buy valuable time for effective management measures to be developed.

FIGURE 2: ANNUAL COSTS OF NON-NATIVE FOREST PESTS IN THE US

Modified from an infographic by Cary Institute. Data from[20].



Biological control: Since the suppression of the invasive Australian pest cottony cushion scale (*Icerya purchasi*) in California's citrus groves by the introduction of the Australian ladybird beetle *Rodolia cardinalis* in the late 1800s, there have been numerous attempts to control insect pests with predators and parasitoids, with varying degrees of success. In the 1980s, the classical approach of introducing alien biological control agents became less popular and more regulated, due to unintended consequences seen in some introductions[35]. A review in 2016 suggested that classical biological control 'has provided and should continue to provide many positive outcomes for dealing with damaging invasive alien insect pests'[35]. Another 2016 review found that, although the number of classical biological control introductions has decreased over the past few decades, successes per introduction are increasing[36]. Non-classical, augmentative biological control is widely used in greenhouses, where biological control agents are released seasonally and not intended to establish permanently.

Pesticides: Insecticides play an essential role in global food security. In 2015, global sales (at the ex-manufacturer level) of insecticides was approximately US$16.7 billion[17]. However, as mentioned above, there is a continual need for more research as the more hazardous pesticides are de-registered or not re-registered by governments and insects evolve resistance.

Genetic modification: Pest resistance is one of the most widely targeted traits in plant genetic modification, with a well-known example being that of plants being modified with Bt toxin from the bacterium *Bacillus thuringiensis*[37]. Pests can evolve resistance to these, but many structures of Bt toxin exist allowing some management of this risk. A 2010 trial of an eradication program in Arizona on a serious cotton pest, the pink bollworm moth (*Pectinophora gossypiella*), combined the release of sterile moths with growing genetically modified Bt-cotton. This combined strategy reduced the need for insecticide sprays and reduced pink bollworm abundance by >99%, with no increase in resistance to Bt-cotton[38].

In summary, insect pests are a global problem for the world's plants. All countries are affected and most are potential sources of new invasive insect pests. To minimise further introductions and spread, we need greater international cooperation, alongside behavioural changes based on an increased awareness of the potential damage to natural capital throughout the world.

BOX 1: *AGRILUS PLANIPENNIS*

The emerald ash borer, *Agrilus planipennis*, is native to East Asia but was found to be killing ash trees (*Fraxinus* spp.) in Michigan and Ontario in 2002; by 2004, 15 million trees were dying[39]. The beetle is thought to have arrived in Detroit on wood packaging material from overseas. Its natural range covers northern China, Japan, and Korea. Asian ash species are resistant to the borer, but the majority of affected American ash trees die. If all of the US's eight billion ash trees die, the cost to forestry will be $282.3 billion and the removal of dead urban trees will cost $20–60 billion[39]. Spread has continued despite efforts at containment. The borer is also killing ash trees in Russia, around Moscow, and is spreading westwards towards Europe[40], where ash populations are already severely challenged by the fungal disease ash dieback.

BOX 2: *DENDROCTONUS VALENS*

The red turpentine beetle, *Dendroctonus valens*, is a secondary pest of pines (*Pinus* spp.). It was first found in China in the 1980s, probably introduced accidentally from America on unprocessed logs. It has spread to infest over 500,000 ha of pine forest in China, killing more than 10 million *Pinus tabuliformis* trees. Warmer winter temperatures in China in the late 1990s may have contributed to its population explosion. A National Management Project was started in 2000, with tight movement controls, adapted silvicultural practices and extensive use of pesticides. This has led to some amelioration of the outbreak. In Shanxi Province, 256,668 ha were infested in 1999, but only 29,913 in 2010[41].

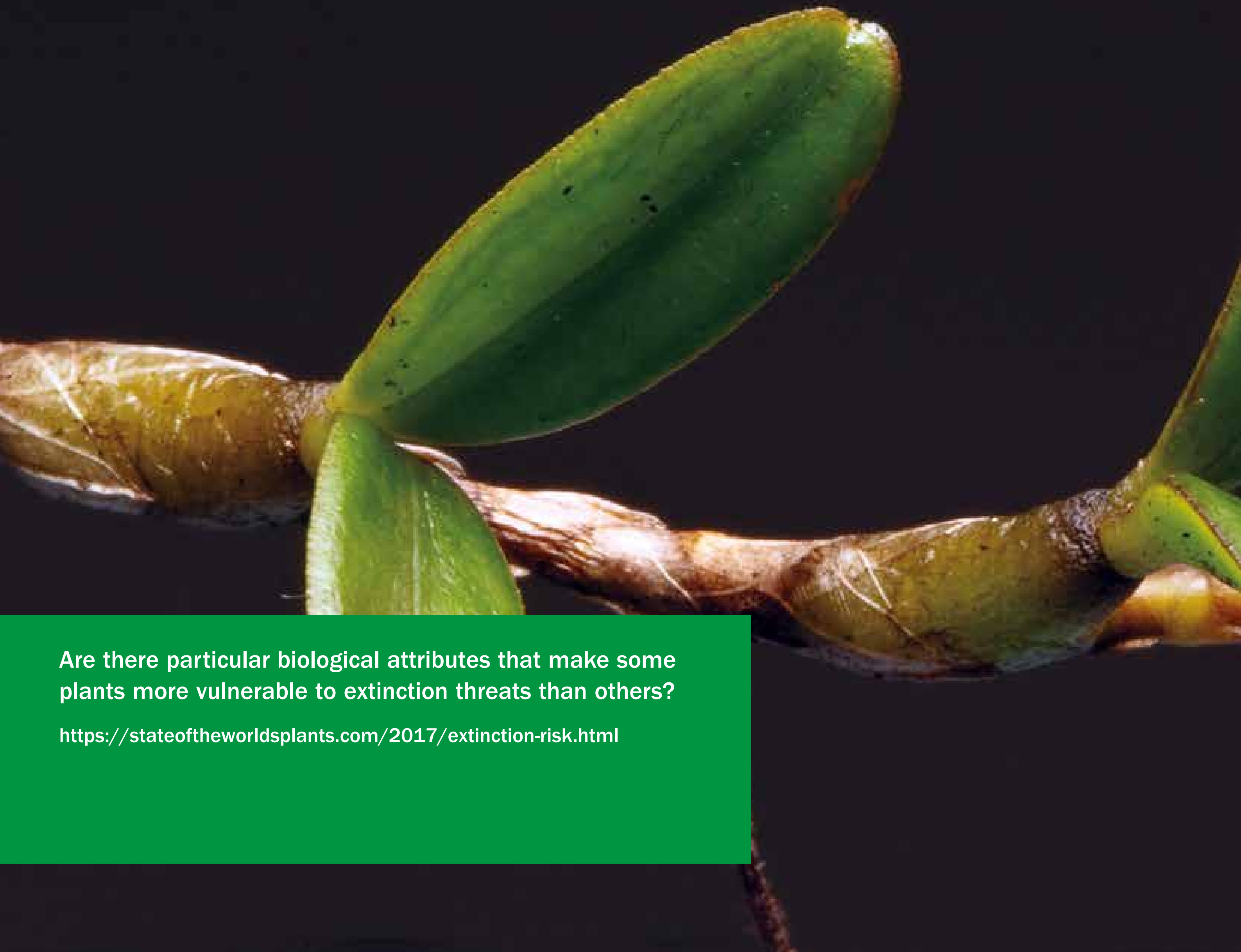
BOX 3: *SPODOPTERA FRUGIPERDA*

The caterpillars of the fall armyworm, *Spodoptera frugiperda*, are highly damaging to many crops, and particularly grasses (maize, rice, sorghum, sugarcane etc.). It is native to tropical and subtropical areas, but adults readily fly long distances and it migrates into temperate areas in the autumn (hence the name fall armyworm). A native of the Americas, in 2016 it was first reported in West Africa and is already spreading rapidly, with newly confirmed reports extending to southern Africa. It is the fastest spreading major pest in the world today in 2017. It can be expected to spread to all suitable areas of Africa within a year or two, as well as threatening to spread to the Mediterranean and Asia.

BOX 4: *TUTA ABSOLUTA*

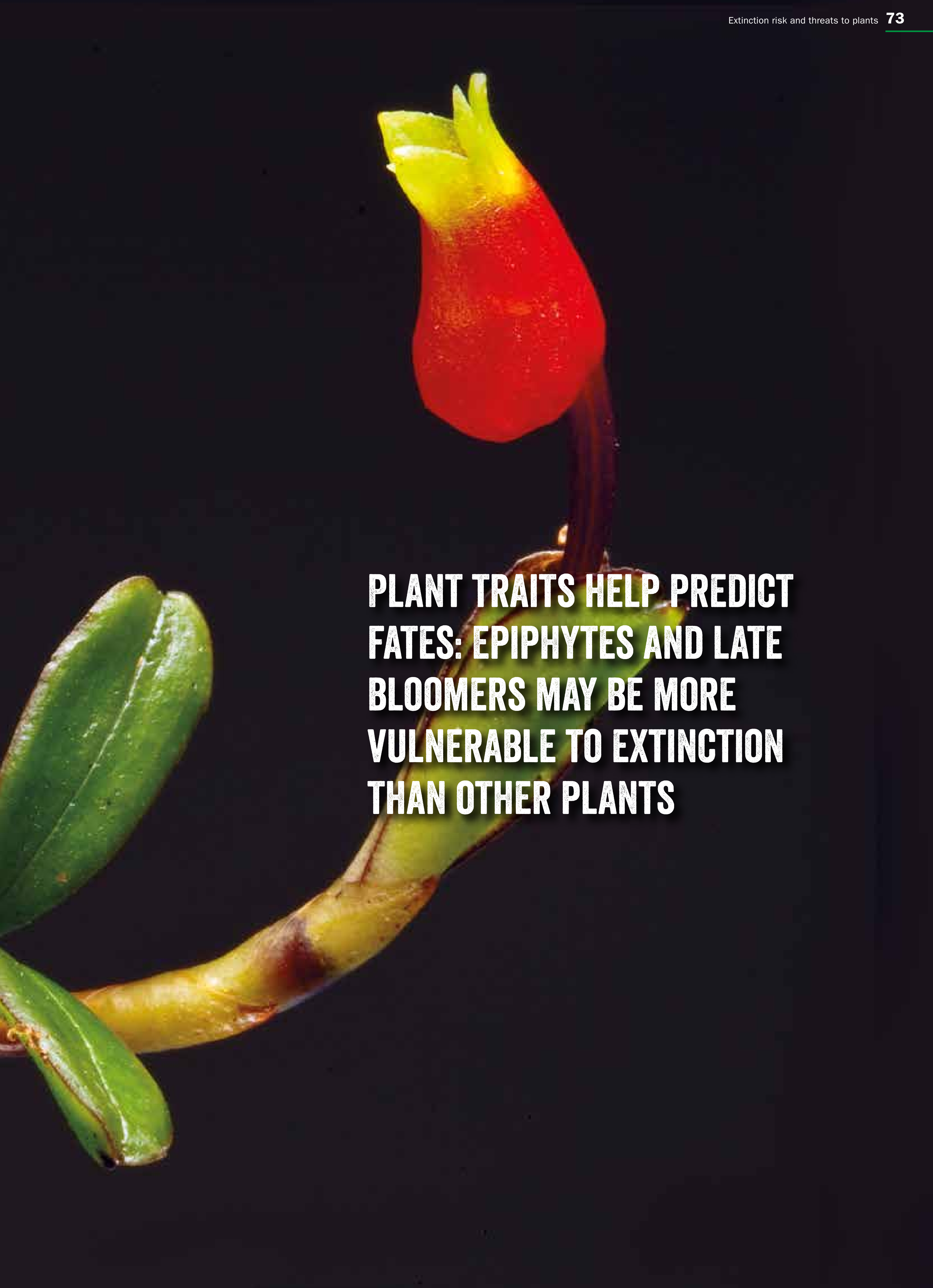
A state of emergency was declared in May 2016 in Nigeria's Kaduna state, due to the moth *Tuta absoluta*, the tomato leafminer. Eighty per cent of farms growing tomato (*Solanum lycopersicum*) were reported to have had their crops destroyed by the pest. The moth is from South America and was found in Europe in 2006, from where it has spread to the middle East and Africa. In 2016, it was reported for the first time in Nigeria, Tanzania, Uganda, Mayotte, Nepal and Bangladesh. Its rapid spread and ability to cause 100% yield loss mean that the tomato leafminer will have a growing impact on global tomato production in coming years. It also highlights that fact that African countries have few defences against invasions by pest from Europe.

EXTINCTION RISK AND THREATS TO PLANTS



Are there particular biological attributes that make some plants more vulnerable to extinction threats than others?

https://stateoftheworldsplants.com/2017/extinction-risk.html



PLANT TRAITS HELP PREDICT FATES: EPIPHYTES AND LATE BLOOMERS MAY BE MORE VULNERABLE TO EXTINCTION THAN OTHER PLANTS

DESPITE ONGOING EFFORTS TO INCREASE THE RATE AT WHICH PLANTS ARE EVALUATED FOR THEIR EXTINCTION RISK, THERE IS WIDESPREAD RECOGNITION THAT MANY PLANTS MAY BECOME EXTINCT BEFORE THEY HAVE BEEN RECOGNISED AS BEING AT RISK, AND PERHAPS EVEN BEFORE THEY HAVE BEEN DISCOVERED[1–4].

Detailed, evidence-based extinction risk assessments of individual species, such as those published on the IUCN Red List of Threatened Species, are vital not only for highlighting species at risk of extinction but also for increasing understanding of the drivers of extinction and for guiding and prioritising management interventions. However, the species-by-species approach can be slow and resource-intensive, and this has driven conservation scientists to search for factors associated with elevated extinction risk in plants that can enable the prediction of extinction risk in the absence of species-specific assessments.

Establishing reliable predictors of extinction risk would be beneficial not only in improving understanding of why some species are more prone to extinction than others, but also in very practical ways, in terms of anticipating management needs. For example, these insights could enable more effective allocation of resources to groups of plants, sites or regions where extinction risk is concentrated[5] or where further assessment is required[6]. Importantly, conservation planning will be better informed by the prediction of extinction risk in relatively poorly understood plant groups and regions. This is particularly true for those species considered data deficient, a large proportion of which are likely to be at elevated risk of extinction[7].

Earlier reviews[8,9] reported more than fifty papers using comparative approaches that seek to identify biological or ecological features (traits) associated with rarity in plants. Fewer than a quarter of these studies involved species with formally documented extinction risk (as distinct from those that are merely ‘rare’), and most treated a single pair of closely related or co-occurring plant species, contrasting threatened and non-threatened species. Comparative studies encompassing larger numbers of plant species with documented extinction risk have mostly focused on temperate floras for which comprehensive species-level extinction risk assessments are available, such as that of Finland[10], the Czech Republic[11], and New Zealand[12]. Continent-scale studies are available for North America (the United States and Canada[13,14]) and for Australia[15]. Large-scale analyses with good representation of tropical species include studies of the Hawaiian flora[16], and the legumes of the world[5]. The trade-off between the number of species included in a study and number of traits that can be scored and analysed, has resulted in studies using only a subset of the potentially informative traits. At the same time, the increasing availability of global species databases appears to have increased the overlap in traits between studies, facilitating cross-study comparison (see also chapter 7 for more detail on traits).

Striking levels of taxonomic pattern in the distribution of extinction risk in certain floras have encouraged scientists to search for inherited traits that might explain these patterns. For example, proportions of threatened species in the most species-rich families in Hawaii are significantly correlated with global proportions of extinction risk in those families[16]. Increased availability of phylogenetic data and analytical methods has facilitated the consideration of relatedness among the species included in large-scale studies, and recent analyses have placed particular emphasis on exploring whether a particular trait is consistently correlated with extinction risk across independent evolutionary radiations[17].

Results to date vary widely, from little or no phylogenetic signal in extinction risk[13,18–20] to distinctively structured phylogenetic signal indicating a concentration of extinction risk in certain groups – for example, young, fast-evolving lineages in South Africa’s unique Cape Flora[21]. While some authors argue that phylogenetic approaches should be used even in the absence of phylogenetic signal in the data[20,22], others argue that phylogenetic and non-phylogenetic approaches should be considered complementary[8,23]. For example, in a large-scale analysis of extinction risk in angiosperms of Brazil’s Atlantic Forest, evolutionary approaches were used to test for evidence of functional relationships between traits and extinction risk, while simple cross-species analyses sufficed for identifying correlates of extinction risk that reflect traits of current ecological relevance[24].

PLANT FUNCTIONAL TRAITS AND EXTINCTION RISK

For those with a practical interest in predicting extinction risk, a key focus has been on plant functional traits (see Box 1), for which data are readily available from published sources such as floristic treatments or online databases. To investigate which plant traits are associated with extinction risk in plants, we considered almost 13,000 publication titles, read more than 3,800 abstracts and reviewed 275 publications in detail, in order to identify > 40 papers whose treatment of plant traits and documented extinction risk qualified them for inclusion in our systematic review. Despite the challenges presented by differences in sample size, trait definition and selection, and analysis methods, we were able to identify some emerging patterns (see opposite).

RELIABLE PREDICTORS OF EXTINCTION RISK
COULD IMPROVE CONSERVATION PLANNING

Our analysis indicates that the following traits seem to be associated with greater risk of extinction:

EPIPHYTES – plants that grow non-parasitically on other plants – have been shown to be at elevated risk of extinction in large-scale studies collectively encompassing thousands of tropical species[24,25].

ZYGOMORPHIC FLOWERS – those with just one axis of symmetry – are associated with elevated extinction risk in temperate floras[14,18].

BIOTIC POLLINATION – in which pollen is transferred between flowers by animals, primarily insects – has been linked to elevated extinction risk in multiple studies[11,14,16,25,26], though not all surveys have detected significant differences[27].

DIOECY – in which male and female flowers are borne on different plants – is associated with elevated extinction risk at a global level[17] but the Australian and Singaporean floras appear to represent exceptions to this global pattern[15,25].

SHORTER FLOWERING PERIODS are associated with higher extinction risk in the large genus *Banksia*[19] and in multi-taxon studies in Finland and the US[10,28], but some species-pair studies report a longer flowering period in the more threatened species of the pair[29,30]. A later start to the flowering season is associated with elevated extinction risk in multiple species-pair studies[28,29,31–34].

LOWER SEED PRODUCTION per unit measured is associated with greater extinction risk in many studies[32,33,35–39], but other similar small-scale comparisons either failed to detect significant differences in seed production[40,41] or found conflicting results[30,42].

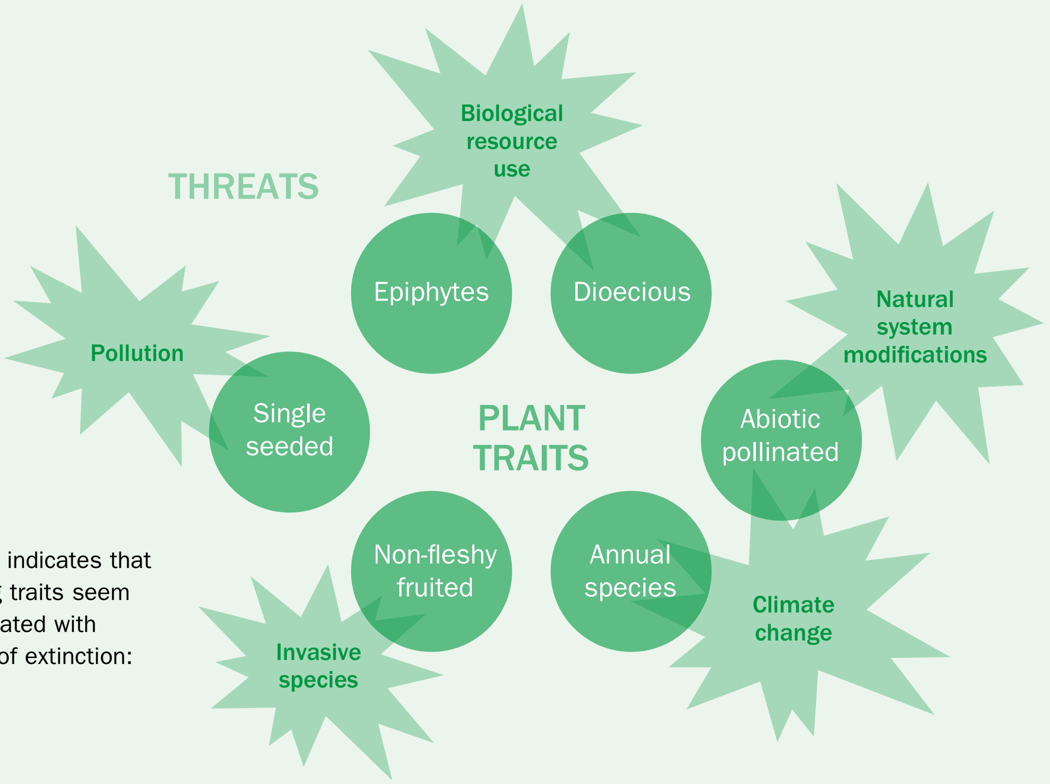
DIPLOIDY – where plants contain just two genomes per nucleus (one from each parent) – is associated with elevated extinction risk in continental and global-scale studies[43,44].

Plant functional traits by themselves do not usually explain much of the variation in extinction risk between plant species[19], but when ecological traits, environmental factors and threats are also considered, the resulting models may lead to a better understanding of extinction risk[45]. For example, in monocots – an ecologically important group, which comprises c.20% of all angiosperms, including economically important families such as grasses, orchids and palms – a recent study of 1,500 species (sampled at random from a global checklist of monocot species) identified epiphytic habit (a plant functional trait) and high altitude (an ecological trait often associated with differences in prevailing bioclimatic or environmental conditions, such as cooler temperatures, increased rainfall, differences in soil quality etc.) as correlates of elevated extinction risk[46]. When the resulting model combining these traits and anthropogenic effects was applied to monocot species either not yet evaluated or classified as data deficient, results indicated that levels of extinction risk in monocots may be twice those currently estimated from species-specific assessments. Practical outcomes of this research include increased investment in evaluating groups currently under-represented on the IUCN Red List, such as the orchids of New Guinea (see Box 2).

Analyses such as those described above show major progress in finding new ways to evaluate extinction risk in plants, speeding up traditional processes and allowing limited resources to be used more effectively, targeting the areas and species that need them most. Looking forward, incorporating consideration of the widest possible range of threats and detailed spatial information into comparative extinction risk analysis will be vitally important to further increase the practical value of these studies[45].

BOX 1: TRAIT–THREAT INTERACTIONS

Interactions between plant functional traits, ecological traits and extrinsic factors drive variation in extinction risk[45]. However, many comparative extinction risk analyses do not consider threats. More qualitative and quantitative data on specific trait–threat interactions will be critically important to improve extinction risk prediction in future. For example, for this report a preliminary analysis of 204 threatened or near-threatened monocot species considered 120 possible trait–threat combinations and found seven significant interactions. Some of these interactions make intuitive sense: an epiphyte-biological resource use interaction reflects the horticultural trade in epiphytic monocots including orchids and bromeliads. Other interactions seem non-intuitive, such as single-seeded species being more likely to be threatened by pollution. These findings prompt further exploration of the data to unpick the underlying mechanisms.



Our analysis indicates that the following traits seem to be associated with greater risk of extinction:

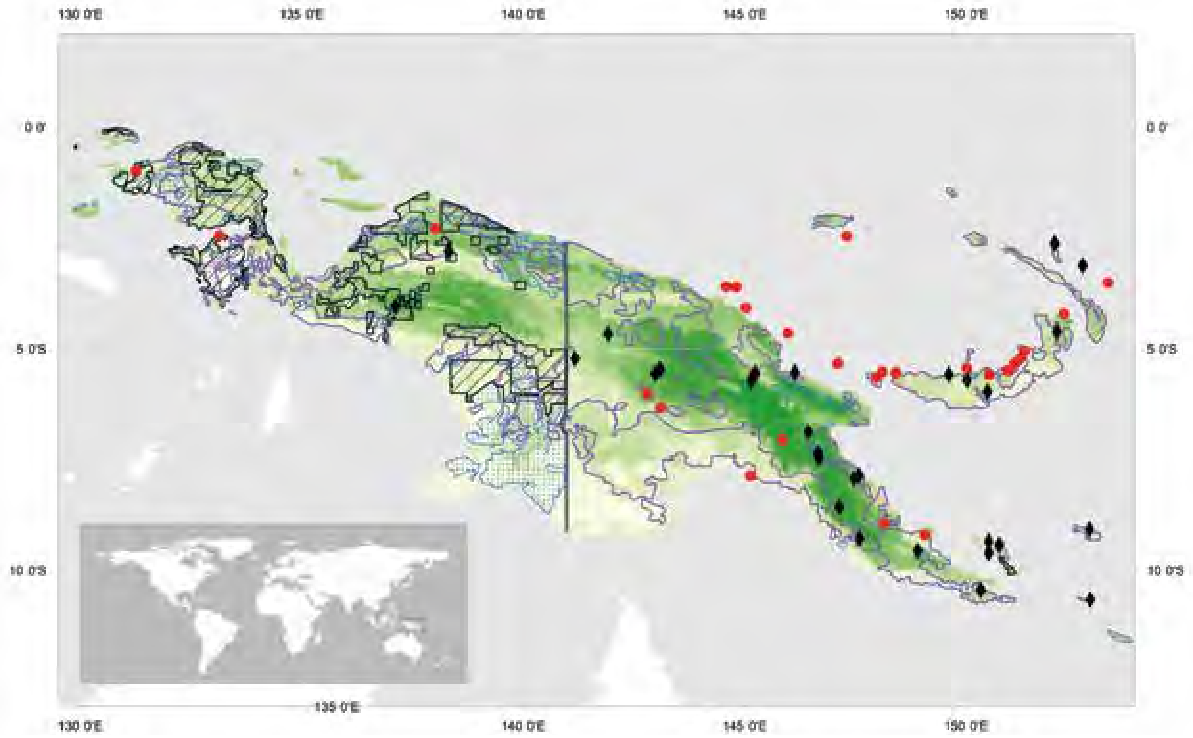
Summary results of an analysis testing correlations between plant traits and threats in threatened or near-threatened monocot species. Only traits and threats showing significant interactions are shown.

BOX 2: UNDER-ASSESSED GROUPS AND AREAS: ORCHIDS AND NEW GUINEA

Orchids are a large plant family of c.29,000 species[47] and are considered among the world's most threatened plants[48,49], but in terms of IUCN Red List assessments they are severely under-assessed, with full global assessments published for only 3% of species. Of the 880 species assessed so far, the percentage flagged as threatened is high at 59%, although this figure is likely inflated due to the bias of focusing assessment effort on species expected to be most threatened with extinction, for example the slipper orchids (Cypripedioideae) [50]. A more accurate estimate of global extinction risk in orchids must await the completion of further assessments, especially from tropical areas that are exceptionally rich in endemic species of this family. One such area, New Guinea, is itself under-assessed on the IUCN Red List, with only c.4% of the estimated 14,000 vascular plant species[51] assessed, 30% of which are considered threatened. There are an estimated 2,800 orchid species in New Guinea, c.95% of which are endemic[52], but again there is severe under-assessment of these, with only 44 species (less than 2%) assessed and published on the IUCN Red List. With increasing threats like the intensification of mining in areas of high orchid diversity, such as the mountainous regions of New Guinea, there is an urgent need to increase coverage of species-specific extinction risk assessments and trait-threat interaction analyses to support conservation activities.

New Guinea orchid
Bulbophyllum nasica

SPECIES RICHNESS AND THREATS TO ORCHIDS IN NEW GUINEA



Threats

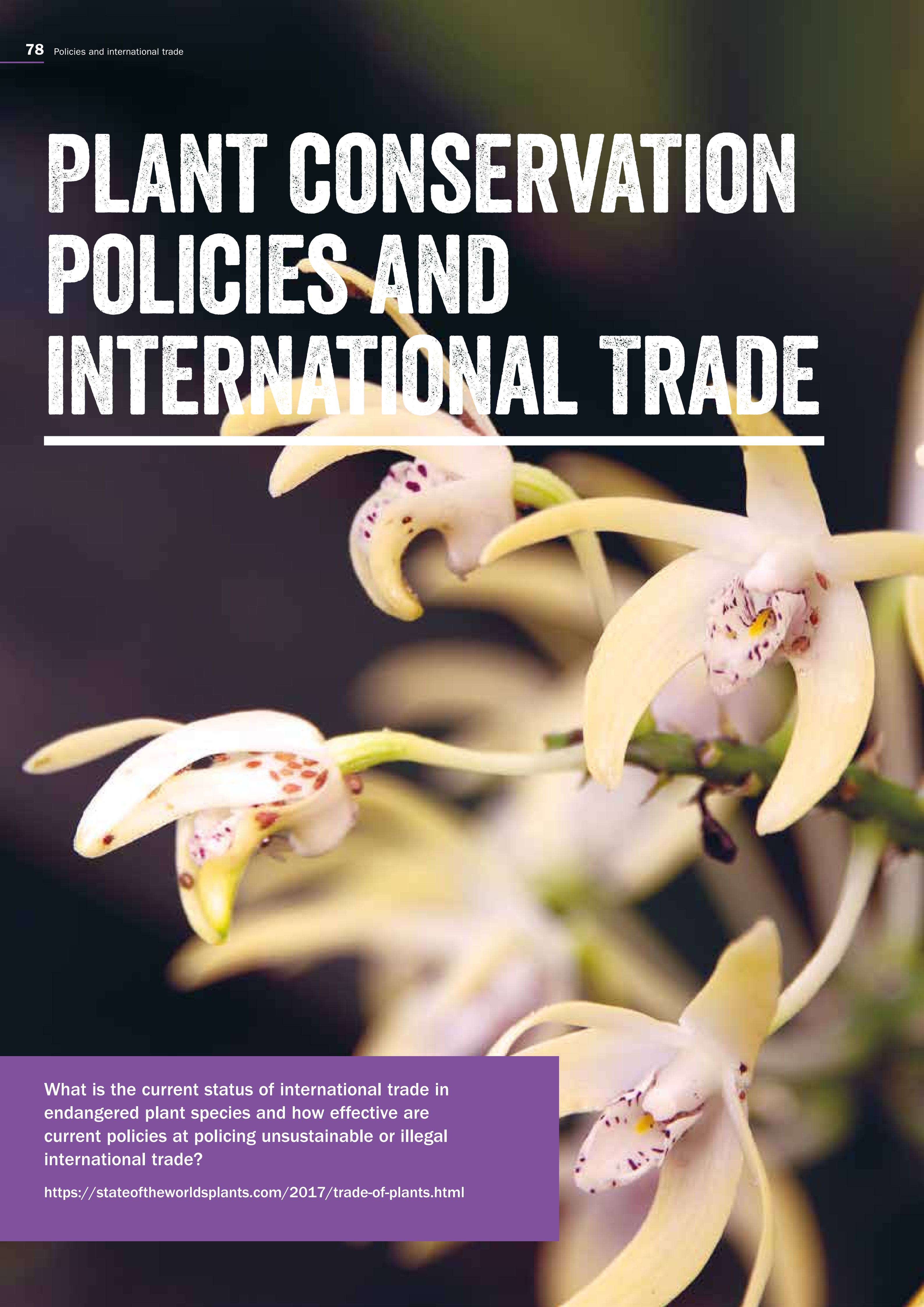
◆ Mines and mining concessions
● Other threats
▨ *Mines and mining concessions*
▨ *Logging activity and logging concessions*
▨ *Other threats*

Modelled Species Richness of Orchids

High: 120 🟩 **Low: 20**

Base map shows number of orchid species (out of the 283 with significant modelled distributions) predicted to occur across the study area of New Guinea. The spatial resolution of the analysis is 5 arc-min, which equates to approximately 9.3 km x 9.3 km near the equator. Modelled richness from Vollering *et al*. (2016)[52]. Symbols and polygons show potential threats to plant diversity.

PLANT CONSERVATION POLICIES AND INTERNATIONAL TRADE



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?

https://stateoftheworldsplants.com/2017/trade-of-plants.html

31,517

PLANT SPECIES ARE CURRENTLY LISTED ON THE CITES APPENDICES

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

2016 WAS AN EXCITING YEAR FOR CONSERVATION POLICY. TWO OF THE MAJOR CONVENTIONS THAT HELP TO PROTECT PLANT DIVERSITY – THE CONVENTION ON BIOLOGICAL DIVERSITY AND THE CONVENTION ON INTERNATIONAL TRADE IN ENDANGERED SPECIES OF WILD FAUNA AND FLORA – HOSTED CONFERENCES TO ADVANCE GLOBAL CONSERVATION AIMS.

It was also the year when the UN Sustainable Development Goals officially came into force[1] (see Figure 1). Here we report on the key outcomes from these conferences, provide an update of plants on the CITES list, and highlight the current status of plant conservation policies in Madagascar.

HIGHLIGHTS FROM THE CONVENTION ON BIOLOGICAL DIVERSITY (CBD) CONFERENCE

The meetings of Parties to the CBD and its two Protocols – the Cartagena Protocol on Biosafety, and the Nagoya Protocol on Access to Genetic Resources – took place in Cancun, Mexico from 2 December to 17 December 2016 (https://www.cbd.int/). The conference had over 7,000 participants from over 170 UN countries, along with representatives from industry, business, academic institutions, NGOs and indigenous people's groups. They examined progress to date on achieving the Aichi Biodiversity Targets and made key decisions to enable the global community to continue to tackle biodiversity loss[2]. Opening the meeting, Mexican President Enrique Peña Nieto stated: 'Either we change our ways of life to stop biodiversity loss or that loss will change forever our ways of life.' A key output from this meeting was the Cancun Declaration. This sets out commitment by the Parties to 'the 2030 Agenda for Sustainable Development and its Sustainable Development Goals, which strongly reflects biodiversity, provides new opportunities to address development challenges in a transformative manner and with a perspective that integrates environmental, economic and social dimensions'[3]. Other agreed objectives were to broaden the remit to include biodiversity in business and develop relevant laws and policies for all sectors of society and the economy.

HIGHLIGHTS FROM THE CITES CONFERENCE

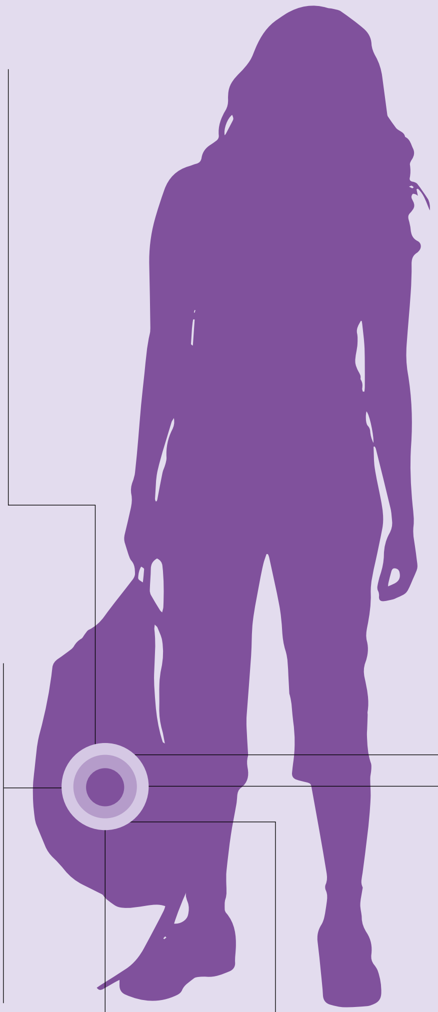
CITES is an international agreement between governments. Its aim is to ensure that international trade does not threaten the survival of plants and animals that are traded. Every three years, the 183 countries (or Parties to the Convention) meet to add, delete or amend species listings on the CITES Appendices. CITES regulates the trade in endangered plant species under three Appendices, and species must meet certain biological and trade criteria in order to be listed. The 17th Conference of the Parties, also known as CoP17, took place in Johannesburg, South Africa from 24 September to 5 October 2016[4].

FIGURE 1: THE UNITED NATIONS DEVELOPMENT GOALS, WHICH OFFICIALLY CAME INTO FORCE ON 1ST JANUARY 2016[36]

SOURCE: HTTP://WWW.UN.ORG/SUSTAINABLEDEVELOPMENT/NEWS/COMMUNICATIONS-MATERIAL/

BOX 1: BIODIVERSITY BLUNDERS IN YOUR BACKPACK – SEIZURES IN 2016[37]

For most species listed in CITES Appendix II, trade is allowed but only with the correct CITES permits. For plants listed in CITES Appendix I, trade is only permitted in exceptional circumstances.



SOME HOUSEPLANTS

orchids, cacti, pitcher plants from local markets

CITES: APPENDIX I & II

ILLEGAL TRADE 2016

ORCHIDS & CACTI

35 of the 220 seizures in 2016 were live plants – 30 orchid seizures, 3 cacti seizures, 1 *Hoodia* sp. and 1 seizure of mixed aloe, cacti and *Euphorbia*

LATEST SLIMMING PILLS

Hoodia (*Hoodia* spp.)

CITES: APPENDIX II

ILLEGAL TRADE 2016

HOODIA

19 of the 220 seizures in 2016 were *Hoodia* pills or powder, which are classified as traditional herbal medicines.

1 seizure of live plants

FOOD SUPPLEMENT AND WORKOUT POWDERS

Dendrobium nobile, an orchid commonly found in protein supplements

CITES: APPENDIX II

ILLEGAL TRADE 2016

ORCHIDS

1 of the 220 seizures in 2016 contained *Dendrobium* spp. as a component of traditional herbal medicine

INCENSE

Agarwood (*Aquilaria* spp.) & *Gyrinops* spp.(14)

CITES: APPENDIX II

ILLEGAL TRADE 2016

AGARWOOD

13 of the 220 seizures in 2016 were agarwood, consisting of 1 carving and 12 products including woodchips

HERBAL MEDICINE

Panax ginseng (Russian Federation populations) & *Panax quinquefolius* (Canada, US, China)

CITES: APPENDIX II

ILLEGAL TRADE 2016

GINSENG

12 of the 20 seizures in 2016 were ginseng classified as traditional herbal medicine

TIMBER CURIOS AND INSTRUMENTS

Dalbergia spp.

CITES: APPENDIX II

Be careful – over 900 timber species are listed on CITES. While most CITES listings just cover commercial trade (i.e. in logs & sawn wood), more recent timber listings cover all parts, including carvings and instruments.

Note that Siamese rosewood differs from other rosewood listings on CITES which do allow 10kg for non-commercial use.

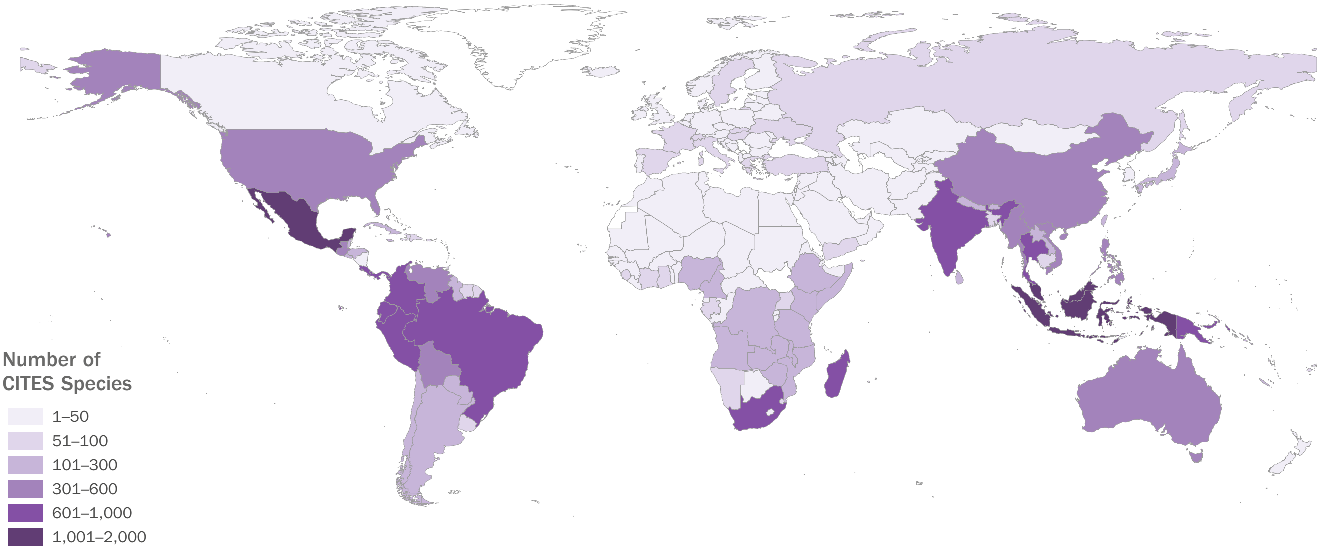
ILLEGAL TRADE 2016

ROSEWOOD

2 of the 220 seizures in 2016 were rosewood guitars

TRADE IN RARE SPECIES SHOWS NO SIGNS OF ABATING, AND CITES PLANT TRADE INTO THE EU IN 2014 WAS WORTH US$286 MILLION, WITH 2,320 PLANT TAXA IMPORTED

MAP 1: NUMBER OF CITES-LISTED SPECIES IN EACH COUNTRY[7]



As a result of CoP17, an additional 304 species have been added to the over 31,517 plant species currently listed on the CITES Appendices. In EU member states, these new CITES listings are legally enshrined by a new EU regulation[5], and there are similar laws in other countries. Trade in rare species shows no signs of abating, and CITES plant trade into the EU in 2014 was worth US$286 million, with 2,320 plant taxa imported[6].

WHICH COUNTRIES CURRENTLY HAVE THE MOST CITES-LISTED PLANT SPECIES?

Indonesia tops the list, with 1,947 CITES-listed plant species, followed by Mexico (1,419), Malaysia (1,056), Ecuador (955), Brazil (921), Colombia (850), Madagascar (818), Papua New Guinea (784), Costa Rica (776) and Peru (709) (see Map 1)[7]. Regions where CITES plant species listings are low but biodiversity is high include West and Central Africa. The rich biological resources of the countries in these regions have not yet attracted much international trade, but there is evidence of increasing trade in forest trees, with the potential for serious negative impacts on West African dry forests[8–11].

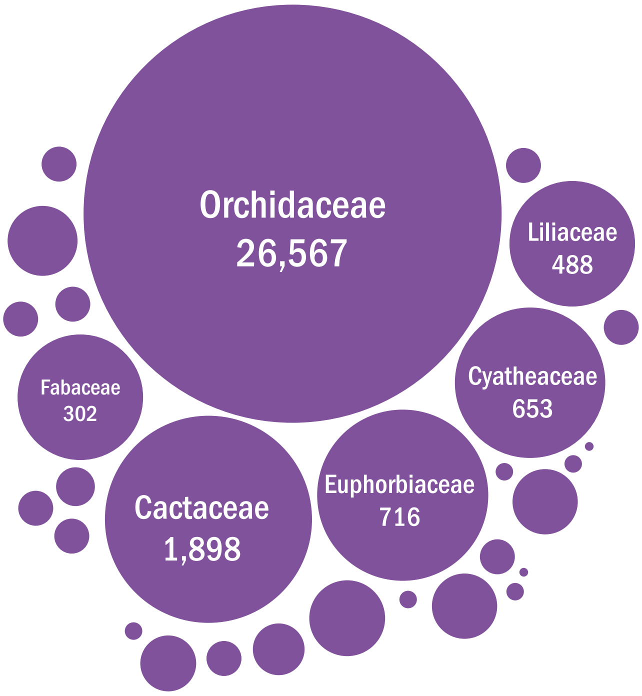
WHICH ARE THE MOST COMMON PLANT FAMILIES LISTED ON CITES?

There are 60 plant families with species listed on the CITES Appendices, ranging from well-known families such as orchids, cacti, and cycads (Cycadaceae & Zamiaceae), to Didiereaceae, which is an unusual family of spiny succulents from Madagascar and Africa. One of the largest plant families, the orchid family (Orchidaceae), dominates the listings on the CITES Appendices, accounting for 84% of listed species (see Figure 2). The desire and interest in these so-called ‘luxury’ plants has led to the coined term ‘orchid mania’; their appeal attracts thousands of visitors to Kew’s orchid festival every year[12]. While orchids for sale as cut flowers and pot plants represent a trade worth millions of pounds[13], over 39 species of orchids in European trade also appear as the components of cosmetic, food and medicinal products[14]. Matching the CITES Appendices checklist[7] of orchids against Kew databases[15] revealed at least 289 uses of orchid species, including medicinal (147 spp.), environmental (111 spp.), as gene sources (59 spp.), materials (10 spp.) and human food (4 spp.), and for social use (2 spp.). Some interesting documented social uses exist for the orchid *Ansellia africana*, which is used as a love charm, as an antidote for bad dreams and to ward off lightning[16]. It is also highly collected and consequently has an IUCN Red List assessment status of Vulnerable. Another unusual use of orchids is in tea. Historically, Bourbon tea was made from the epiphytic orchid *Jumellea fragrans*, found on the islands of Reunion (formerly known as Bourbon) and Mauritius. This beverage was highly popular 80–100 years ago[17].

The next largest family group listed on the CITES Appendices is Cactaceae[7] (see Figure 2), with 1,898 species. More than half of all cactus species are estimated to be used by people. The most common stated use is ornamental horticulture[18] but food is another; for example prickly pear (*Opuntia* spp.) is commonly used as food[19]. Matching the CITES Appendices checklist[7] of cacti species against Kew databases[15] reveals there are currently 231 cacti species with uses. These include species with medicinal uses (65 spp.), environmental uses (152 spp.) and social uses (10 spp.), in addition to animal food (29 spp.), human food (89 spp.), materials (43 spp.), fuels (11 spp.), gene sources (9 spp.), poisons (4 spp.) and even invertebrate food (1 spp.). Our world would have a lot less colour without *Dactylopius coccus*, a scale insect which feeds on *Opuntia* and from which the natural red dye carmine or cochineal was first derived, used and discovered by the Aztec and Mayan civilisations[20]. The dye has become popular again, as many commercial synthetic red dyes have been found to be carcinogenic[21].

FIGURE 2: FAMILY GROUPS PROTECTED UNDER CITES CONVENTION

Number of CITES species shown for each family. Developed using data from UNEP-WCMC (Comps.) (2015) & Orchid data Kew (2017).



HOW WELL IS CITES DOING IN TERMS OF COMBATTING ILLEGAL PLANT TRADE?

This issue is difficult to fully assess globally, but as a snapshot of trade in illegal plants in the UK we obtained data of plant seizures in 2016 by the UK Border Force at Heathrow Airport, London. This revealed that 220 individual CITES-related plant seizures were made in 2016 (Figure 3).

Live orchid plants dominate the seizures, followed by plants used in traditional medicines and healthcare products. This pattern is similar to other studies, indicating that the illegal trade in plants the world over is dominated by orchids[22–26].

THERE ARE 1,898 CACTACEAE SPECIES LISTED ON THE CITES APPENDICES

A key question is why is this illegal trade in plants occurring? While there is an internet-driven trade in wild plant species, especially for the horticulture industry[22,23,27], many incidents of illegal plant materials seized at Heathrow show that the passenger is often unaware of the legislation and protection surrounding CITES-listed species and products (see Box 1). This indicates an urgent need for better education for travellers, especially those visiting regions of threatened plant diversity.

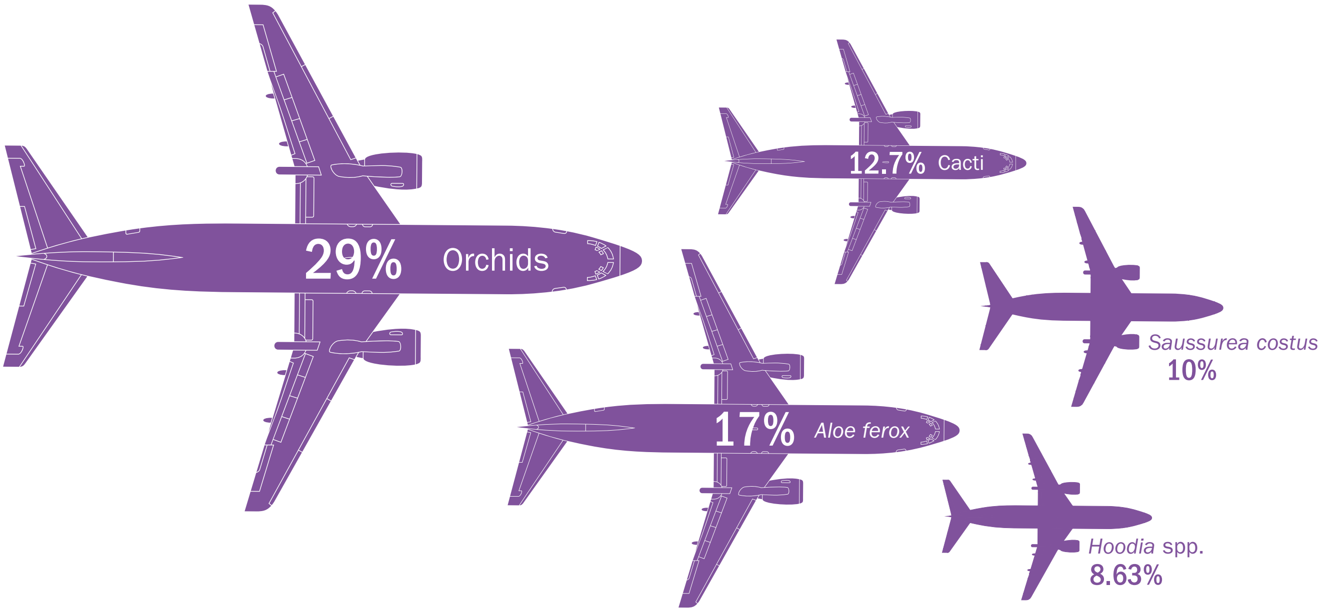
PLANT CONSERVATION POLICIES IN MADAGASCAR

With the country focus of this year's report on Madagascar, we examined the current status of their conservation policies. Madagascar has long been regarded as a high priority for plant conservation[28–31]. In a recent IUCN Red List assessment of the conservation status of the flora, 1,676 species were classified as At Risk and one group, the palms, was classified as Highly Threatened[32] (see chapter 6).

Madagascar also has the highest global percentage of its total flora listed on CITES (8.6%), followed by Malaysia and Papua New Guinea (6.8%) (Map 1). Madagascar's wild plants are particularly under threat from trade in timbers, food products, cosmetics and horticulture. The internet is playing an increasing role in this trade, with 85% of recently-listed endemic succulent species from Madagascar being offered for trade online for horticulture[27].

At the 2016 CITES Conference of the Parties[33], two important steps were made to further protect Madagascar's iconic flora from illegal trade. First, Madagascar agreed, with the support of the CITES Parties, a set of decisions to effectively manage their timber stockpiles of precious timbers from *Dalbergia* spp. (rosewoods) and *Diospyros* spp. (ebonies). Second, Madagascar's endemic *Adansonia grandidieri* (Grandidier's baobab – featured on the cover of this year's report and one of six threatened endemic *Adansonia* species in Madagascar) was added to the CITES Appendices. Baobab fruits are exported for their use in food and cosmetic products[34]. It is critical that trade in this plant is managed sustainably; much of its native habitat has been cleared and it has very low natural regeneration[35]. The addition of *Adansonia grandidieri* to the CITES Appendices will ensure international trade of this iconic species is regulated. This example is a good illustration of the importance of international policies and global government commitments: they ensure that unique plant biodiversity has global support and that procedures are in place to protect, highlight and recognise their true value.

FIGURE 3: CITES PLANT-RELATED SEIZURES AT HEATHROW IN 2016[37]



The data reveal that orchids make up 29% of all plant and plant-derived products confiscated, followed by *Aloe ferox* (17%), cacti (12.7%), *Saussurea costus* (10%) and *Hoodia* spp. (8.63%). The total number of CITES plant-related seizures by the UK Border Force Heathrow Team in 2016 was 220. Of these, 121 seizures related to health supplements or traditional medicines, 40 to plant parts or derivatives, 35 to live plants, 18 to timber or wood products and 6 to cosmetics. Thailand, the US and China were the three main sources of seizures.

Contributors and references

Authors are affiliated to RBG Kew unless otherwise stated. The production of this report has been supported by numerous staff members at Kew, our partner organisations, and many other individuals.

1. Naming and counting the world's plant families

Authors: Rafaël Govaerts, Dr Nicholas Hind, Heather Lindon, Prof. Mark Chase, Dr William Baker, Dr Gwil Lewis, Dr Maria Vorontsova, Nicky Nicolson, Dr Maarten Christenhusz, Dr Abigail Barker and Dr Alan Paton

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2 New plant species discovered in 2016

Authors: Dr Martin Cheek, Heather Lindon and Dr Eimear Nic Lughadha

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3. Plant genomes – progress and prospects

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4. Useful plants – medicines

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5. Important Plant Areas

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6. Country focus – status of knowledge of Madagascan plants

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7. Climate change – which plants will be the winners?

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8. Global land-cover change – wildfires

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9. Invasive species

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10. Plant health – state of research

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11. Extinction risk and threats to plants

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12. Plant conservation policies and international trade

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