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Plant diversity in a changing world: Status, trends, and conservation needs

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ABSTRACT

The conservation of plants has not generated the sense of urgency—or the funding—that drives the conservation of animals, although plants are far more important for us. There are an estimated 500,000 species of land plants (angiosperms, gymnosperms, ferns, lycophytes, and bryophytes), with diversity strongly concentrated in the humid tropics. Many species are still unknown to science. Perhaps a third of all land plants are at risk of extinction, including many that are undescribed, or are described but otherwise data deficient. There have been few known global extinctions so far, but many additional species have not been recorded recently and may be extinct. Although only a minority of plant species have a specific human use, many more play important roles in natural ecosystems and the services they provide, and rare species are more likely to have unusual traits that could be useful in the future. The major threats to plant diversity include habitat loss, fragmentation, and degradation, overexploitation, invasive species, pollution, and anthropogenic climate change. Conservation of plant diversity is a massive task if viewed globally, but the combination of a well-designed and well-managed protected area system and *ex situ* gap-filling and back-up should work anywhere. The most urgent needs are for the completion of the global botanical inventory and an assessment of the conservation status of the 94% of plant species not yet evaluated, so that both *in* and *ex situ* conservation can be targeted efficiently. Globally, the biggest conservation gap is in the hyperdiverse lowland tropics and this is where attention needs to be focused.

1. Introduction

The conservation of plant diversity has received considerably less attention than the conservation of animals, perhaps because plants lack the popular appeal of many animal groups (Goettsch et al., 2015). As a result, plant conservation is greatly under-resourced in comparison with animal conservation (Havens et al., 2014). Yet plants are much more important to us. Animals can provide meat, leather, fur and other products, but none of these are necessities for human survival and well-being, while many plant products are essential. Plants provide food for us and our livestock, as well as a huge diversity of other products and services, from timber and fibers to clean water and erosion control. Although most commercial plant products come from a very narrow range of plant species, a life based on only these species would be both unhealthy and dull: even urban dwellers use a wide range of other plant species for various purposes and rural people tend to use many more. Wild plant foods contribute to nutrition and food security, and numerous additional species have roles in traditional medicine. Moreover plants are the basis for all terrestrial ecosystems, providing the three-dimensional structure in which animals live and move, and the food on which a majority feed.

This review focuses on the current status of global land plant diversity, the major threats to its continued persistence, and the priority actions for its conservation. It concentrates on the tropics, where most plant species live but least is known about them.

2. How many plant species are there?

The updated Global Strategy for Plant Conservation (hereafter GSPC) agreed at the CBD meeting in Nagoya in 2010 to include, as its first target for 2020, 'an online flora of all known plants' (www.

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cbd.int/gspc/targets.shtml). This target is perhaps achievable, but it explicitly omits unknown species, of which there are still many. A recent paper estimated the total number of angiosperm species at around 450,000, of which 10–20% are still unknown to science (Pimm and Joppa, 2015). Recent estimates for gymnosperms (1000 species; Christenhusz et al., 2011), ferns (10,000 species; Ranker and Sundue, 2015), lycophytes (1300 species), mosses (9000 species; Magill, 2010), hornworts (200–250 species; Villarreal et al., 2010), and liverworts (7500; Von Konrat et al., 2010) suggest that the global total for all land plants is around 500,000 species. This compares with around 10,000 bird species and 5400 mammals. Indeed, the only taxonomic groups whose diversities are thought to substantially exceed that of land plants are the largely plant-dependent fungi (1.5–5.1 m; Hawksworth, 2012) and beetles (ca. 1.5 m; Stork et al., 2015).

3. Where are they?

Pimm and Joppa (2015) estimated that two-thirds of all angiosperm species are found within the tropics. Fern diversity is even more highly concentrated in the tropics (Kreft et al., 2010) while, among the bryophytes, liverwort diversity is highest in the tropics but mosses show no clear latitudinal gradient (Geffert et al., 2013; Chen et al., 2015). The distribution of plant species across the tropics is far from uniform, with the highest diversities in the Neotropics and the Asia–Pacific region, and lower diversities in Africa and on oceanic islands. For example, Slik et al. (2015) estimate that there are 40,000–53,000 tree species in the tropics—96% of all the tree species on Earth (Poorter et al., 2015) —with similar numbers (19,000–25,000) in the Neotropics and the Asia–Pacific, but far fewer (4500–6000) in Africa. Although plant diversities are lower on individual islands, endemism is high and around 50,000 species of vascular plants are island endemics (Sharrock et al., 2014). Also, not all concentrations of plant diversity are tropical: regional diversity is also very high in the Mediterranean region and in similar climates elsewhere, as well as in the moist subtropical areas of Asia (Barthlott et al., 2007; Joppa et al., 2013). At higher spatial resolutions, the concentration of plant species is even more marked, with 67% of all plant species confined to, and 81% present in, only 17% of the Earth's land surface (Joppa et al., 2013).

For trees, there is enough data from plot inventories to look at patterns of local diversity on a regional scale. For example, within tropical East Asia (SE Asia plus S China and NE India), the highest diversities (>210 tree species >10 cm diameter in 1 ha of forest) are in lowland rainforests in Borneo and Sumatra, but high diversities (>100 tree species) also occur in lowland rainforests from Sulawesi to southern China (Corlett, 2014a). Plots at higher altitudes (>1200 m), on extreme soil types, and in areas with a long dry season have lower tree diversities, as do all sites north of the tropics. The contrast between tropical and temperate zone tree diversity is highlighted by the fact that just 52 ha of lowland rainforest at Lambir in Borneo supports as many tree species (1175) as all the temperate forests in the northern hemisphere together: Asia, Europe and North America (Wright, 2002). Similar diversity patterns occur in other tropical regions, with land plant diversity best predicted by the number of wet days per year (Kreft and Jetz, 2007).

4. Do we need them all?

The conservation of all plant species can be justified on a range of aesthetic, scientific and ethical grounds - it is simply good stewardship - but these arguments seem to have been used more effectively in support of animal conservation. Unlike butterflies or frogs, plants are expected to be useful. In low-diversity ecosystems, most plant species do have specific human uses that justify their protection, but this is not true in the hyperdiverse tropical forests, where local people appear to know only a subset of the flora (personal observations in Papua New Guinea and SE Asia). The use of relatives of species with specific human uses in plant breeding programs considerably extends the list of 'useful' plant species. For example, a recent study in China identified 871 species of wild relatives of major crops (Kell et al., 2015), although this is still a relatively small proportion of China's total angiosperm flora of around 30,000 species (Wang et al., 2015). All wild plant species, however, are parts of natural ecosystems which, in turn, provide services for human populations. Are they all necessary for ecosystems to function?

High local plant diversities in tropical forests have been explained in multiple ways, with most of these depending on differences between species, in their resource use (water, nutrients, light) and/or in their pests and diseases (Wright, 2002; Corlett, 2014a). Neutral theory, in contrast, suggests that coexistence depends on the ecological equivalence of species rather than their differences (Rosindell et al., 2012). The available evidence strongly supports the idea that coexistence depends on differences (Corlett, 2014a), but this does not necessarily imply that these differences are important to the maintenance of ecosystem functioning. In the most species-rich forests, most species are rare and the common species are likely to dominate ecosystem functions. For example, a remarkably few, common, large tree species (1.5% of the total tree flora in both the Amazon Basin and Central Africa) contribute disproportionately to carbon storage and fluxes in tropical forests (Fauset et al., 2015; Bastin et al., 2015). However, a recent study showed that the rare species in high diversity ecosystems support the most distinctive and vulnerable functions, and that these species make a disproportionate contribution to the potential range of functions that can be provided by the ecosystem (Mouillot et al., 2013). In an era of rapid global change, this functional redundancy is likely to be a useful insurance policy against unpredictable threats.

5. How many species are threatened?

Target 2 of the GSPC is assessing the conservation status of all known plants by 2020, but we are still a long way from achieving this. Fewer than 20,000 plant species have been formally assessed so far at the global level using the IUCN Red List criteria, so the proportion of land plants that are threatened is not accurately known. Pimm and Joppa (2015) suggest that a third of all angiosperms are at risk of extinction, including most of those that have not yet been described, since these are likely to have small ranges and be locally rare. Brummitt et al. (2015) assessed the status of a random sample of 7000 plant species against the Red List criteria, including bryophytes, ferns, gymnosperms and angiosperms (represented by monocots and the well-studied legumes) and concluded that 22% were threatened (IUCN categories Vulnerable, Endangered, or Critically Endangered) and 30% threatened or near-threatened. For the major groups assessed, the percentage threatened ranged from 11% for legumes to 40% for gymnosperms. Compared with other groups assessed in the same way, plants are more threatened than birds, similar to mammals, and less threatened than amphibians.

Note, however, that this sampling approach necessarily excludes the species still unknown to science and thus almost certainly underestimates the overall threat levels. Moreover, Data Deficient species were assumed to be threatened in the same proportions as those with enough information, while it is more likely that data deficiency most often reflects rarity and thus higher vulnerability. The habitat with most threatened species was overwhelmingly tropical rainforest in both the above studies. A recent model-based assessment of the conservation status of 15,200 Amazonian tree species estimated that 36%–57% would likely qualify as threatened under IUCN Red List criteria and the authors go on to suggest that the majority of the world's >40,000 tropical tree species may be threatened (ter Steege et al., 2015). If these estimates are confirmed, it suggests that tropical trees are among the most threatened taxa on Earth.

In contrast to threat assessments, known global extinctions among plant species are still few. The current IUCN Red List of Threatened Species (Version 2015-3. www.iucnredlist.org Downloaded on 26 December 2015) includes only 139, of which 37 still survive in cultivation. This compares with 140 bird and 78 mammal species, out of much smaller total numbers. The IUCN warns that all these numbers are 'likely to be significant underestimates' and lists another 113 species as 'Possibly Extinct'. This informal list, which is dominated by plants, was developed to highlight Critically Endangered species that cannot be listed as Extinct without additional surveys, and it shows the difficulty in determining if a rare plant species is extinct or not. Plants don't sing or come to baits, and don't walk past camera traps, which makes it much more difficult and time-consuming to assess their conservation status than it is for vertebrates and some invertebrates. There are an estimated 1.4 trillion individual trees >10 cm in diameter in the tropical and subtropical forests that harbor most of the world's plant diversity (Crowther et al., 2015), and trillions more small trees, shrubs and herbs, so it is easy to overlook the last few individuals of a threatened species, particularly when the key characters for identification are high up in the canopy, as is true of most large trees, or only visible for a brief period each year, as is true for many smaller plants.

6. What are the major threats?

6.1. Habitat loss, fragmentation, and degradation

Habitat loss and associated fragmentation is the biggest single threat to plant diversity, particularly in the tropics (ter Steege et al., 2015), where conversion of tropical forests to pastures and commercial crop monocultures (oil palm, rubber, soy etc.) has replaced small-scale cultivation by poor farmers as the major driver of forest loss. Few forest-adapted plant species survive complete deforestation, and even if a substantial fraction of the original forest cover remains, fragmentation drives changes that tend to reduce plant diversity (Kettle and Koh, 2014). Large areas of the remaining forest, whether fragmented or not, are degraded by logging, fire, and other impacts, including fuelwood harvesting in densely populated areas (Specht et al., 2015). Non-forest habitats, from savannas and grasslands to deserts, are similarly threatened by agricultural development. Many plant species are confined to specialized habitats, such as limestone or ultramafic outcrops, which are unsuitable for commercial agriculture, but such habitats often have different, highly specific threats, such as mining of limestone to make cement (Clements et al., 2006) and of ultramafic rocks for nickel (Losfeld et al., 2015), which are particularly damaging because of the small areas involved.

6.2. Overexploitation

Overexploitation—of the whole plant or enough of it to reduce the chance of survival—is the second most important threat to plant species. It is usually more or less species-specific, although some species can be lumped together for specific uses, for example dipterocarps with similar wood in the timber trade or plants with similar properties in the medicine trade. People collecting plants for home use or for sale face the same difficulties in locating them as botanists do, so exploitation to the point of extinction is likely only in species with a restricted range or where the value increases with rarity, as will often be the case for luxury products. Collection for the horticultural trade and for private collections is the biggest single threat to the cacti (Goettsch et al., 2015) and, in many areas, orchids (Phelps and Webb, 2015), as well as cycads and ornamental species in many other families (Sharrock et al., 2014). Extinction is also likely to be slow where only the largest individuals are harvested, as happens with timber trees, since seedlings, saplings and undersize adults survive each round of logging. Logging affects more than half of all remaining tropical forests (Sharrock et al., 2014), but over-logging threatens the timber supply long before it threatens individual tree species (Shearman et al., 2012). Damage from the harvesting of non-timber forest products (NTFPs) varies widely, depending on whether whole plants are removed or killed, and, if only parts of each plant are removed, how this affects growth, reproduction and survival. Note that overexploitation of animals may also threaten plant species in the long term, by restricting seed dispersal (e.g. Harrison et al., 2013) or, in some cases, pollination.

6.3. Invasive species

Invasive alien species are another potential threat to native plant diversity. A recent study showed that more than 13,000 species—3.9% of the world's vascular plant flora— have become naturalized somewhere outside their native range as a result of human activity (van Kleunen et al., 2015). Tropical regions generally have fewer naturalized species than temperate regions, but these numbers are increasing as direct trade between tropical countries overcomes the geographical barriers that have isolated the major tropical regions during the period when most modern species evolved (Corlett and Primack, 2011). Although invasive plant species can have massive local impacts, reducing native plant diversity, and changing fire regimes and nutrient cycling (Pyšek et al., 2012), we actually know very little about their longer-term impacts on regional and global plant diversity. Even on oceanic islands, where local impacts tend to be much greater than on the mainland, non-native plants generally add to the total plant diversity, rather than replacing native species, and in continental areas there is little evidence that invasive plant species currently threaten any native species with extinction (Ellis et al., 2012; Thomas and Palmer, 2015). It is possible that competitive exclusion of native species is simply very slow (Gilbert and Levine, 2013), but current evidence suggests that, despite often large local impacts, the extinction risk from invasive plants is low. Invasive animals may be more of a threat, particularly generalist herbivores, such as goats, on islands that lack native vertebrate grazers and browsers (Chynoweth et al., 2013).

6.4. Air pollution and nitrogen deposition

Every plant on Earth today is exposed to an atmosphere that differs significantly in composition from any that its ancestors would have experienced. Changes in the concentration of the major greenhouse gases (CO_2, CH_4, N_2O) are considered separately below, but other air-borne pollutants can also impact plant diversity (Corlett, 2014b). The major source of air pollution is the burning of fossil fuels and the most important primary pollutants are sulphur dioxide and nitrogen oxides. Ozone, which is produced from hydrocarbons and nitrogen oxides in the presence of sunlight, is the most important secondary pollutant. Particulates (or aerosols: solid and liquid particles suspended in the air) are derived from a variety of primary and secondary sources. Air pollution is declining in Europe and other developed regions, but increasing in much of Asia. Wet and dry deposition of nitrogen compounds not only acidifies the soils but can also dramatically change nutrient cycles, as has happened over much of southern China, with a largely unknown impact on plant diversity (Zhu et al., 2015). Indeed, for tropical forests in particular, our current understanding of the impacts of air pollution and nitrogen deposition on plant diversity is very limited.

6.5. Climate change

The impacts of anthropogenic climate change are also complex and unpredictable, and even more pervasive. After around 1 °C of global warming so far, many temperate zone plants are leafing and flowering earlier in spring and—less consistently—delaying leaf fall in autumn (Ge et al., 2015). Some species have extended their ranges towards the poles and/or to higher altitudes, although other species have not done so (Hijioka et al., 2014). Growth rates have generally increased where temperature is limiting and decreased where water is. Although no global plant extinctions have yet been attributed to anthropogenic climate change, there is evidence that local extinctions have occurred at the climatic margins of species ranges (Buse et al., 2015).

The recent Paris Agreement (UNFCCC, 2015), signed (but not yet ratified) by 195 countries, set a target of keeping "the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels", but the pathway to these ambitious targets is still unclear. Without rapid cuts in emissions, 3–4 °C is more likely. Even a 2 °C rise in global temperature means generally greater warming of land surfaces, particularly at high northern latitudes, and will be associated with less predictable changes in rainfall and other climatic parameters (IPCC, 2013). Climate change will also interact with other impacts: both negatively, as with fires and fragmentation, but also perhaps positively with rising carbon dioxide levels (Corlett, 2014b). When changes in the local climate exceed the range of natural variation, plant populations can either acclimate (i.e. adjust physiologically within the lifetime of an individual), adapt (by evolutionary changes over multiple generations), move to somewhere with a more suitable climate, or die. There is very little information available on either acclimation capacity or evolutionary potential for all but a few model plant species, but the capacity for movement is better – although still incompletely – understood (Corlett and Westcott, 2013; Corlett, 2015). These studies suggest that most plant species will find it difficult or impossible to track the expected rate of climate change, except in steep topography where climatic gradients are equally steep. Moreover, some current climatic conditions cannot be tracked, since they will completely disappear, while large areas of tropical and subtropical lowlands will have climates by the mid to late 21st century that do not currently exist anywhere on Earth (IPCC, 2013).

7. How can they be conserved?

Viewed globally, conserving plants is a huge job: 500,000 species spread over the Earth's land surface, of which 100,000–160,000, many currently unknown to science, may be threatened. The fact that most species and most threatened species are in tropical rainforests has been a problem for their conservation, since most conservation expenditure and the most ambitious plant conservation projects are in high-income countries outside the tropics. However, rapid economic development in recent years has lifted most tropical rainforest countries in Asia and the Neotropics, and some in Africa, into the middle-income bracket, so they have more financial and other resources potentially available for conservation, even if they are not currently using them for this. International donors are still an important source of funding for conservation in some of these countries, but national governments are in the best position to provide the continued baseline support that is likely to be most effect in the long term.

7.1. Completing the inventory

The most urgent task is to complete the inventory of all land plant species. We need a complete global list of species, including the estimated 50,000–100,000 species that not yet been collected and described (i.e., overcome the Linnean shortfall), and determine their distributions (the Wallacean shortfall), as well as understand their phylogenetic relationships (the Darwinian shortfall) (Diniz-Filho et al., 2013). We also need to make this information easily accessible on-line (Meyer et al., 2015). GSPC target 1, 'to produce an online flora of all known plants', covers much of this, but it does not include a strategy for ensuring that as many as possible of the currently unknown plants become known by 2020. Moreover, the short time-frame means that, in practice, the first global flora will largely be a compilation of existing information. Recent studies suggest that spatial bias in collection activity in botany is idiosyncratic, with large under-collected areas—particularly in the tropics—as well as pockets of intense activity (Vale and Jenkins, 2012; Yang et al., 2014).

7.2. Conservation status assessment

Only slightly less urgent is a global assessment of the status of the 94% of land plant species not yet evaluated globally under the IUCN Red List criteria, so that both *in* and *ex situ* conservation can be targeted efficiently. A recent assessment of all but two of the large family Cactaceae (1480 species), in which only 11% of species had been evaluated before 2013, suggest that this goal is no less achievable for at least some plant groups than it is for animal groups, such as the amphibians, which have received much more conservation attention (Goettsch et al., 2015). Clearly botanists need to make this a higher priority than it is at present. A preliminary assessment of the global status of 15,200 Amazonian tree species, using spatially explicit models of tree species abundance and deforestation, and interpreting the results using the IUCN Red List criteria, demonstrates the potential for scaling up the assessment process, although the authors point out that species-by-species assessments are still needed (ter Steege et al., 2015). Regional and national assessments using IUCN Red List criteria include many species that have no global assessment yet, and can provide a basis for targeting conservation work in these areas (Havens et al., 2014; Sharrock et al., 2014).

7.3. Improving the protected area system

When we know what is threatened we can assess current protected area systems and add to them where they provide inadequate *in situ* coverage, as will be true in most areas. However, assessing the adequacy of existing coverage of threatened plants is difficult in most of the world, because inventories are lacking (Sharrock et al., 2014). In response to this information gap, the Royal Botanic Gardens Kew is proposing to identify and map 'Tropical Important Plant Areas' (TIPAs) which support high concentrations of threatened species (www.kew.org/science-conservation/kews-science-strategy/2020-strategic-outputs/tropical-important-plant-areas). Currently an estimated 15% of the Earth's land surface is legally protected for conservation, but coverage varies widely among ecosystems, as does the effectiveness of the protection. General reviews of the effectiveness of protected areas in conservation show that they retain more biodiversity than alternative land uses (Coetzee et al., 2014) and that management effectiveness is generally increasing (Geldmann et al., 2015), but there have been no long-term studies of their ability to maintain viable populations of threatened plant species. A review of tropical forest reserves found mixed results and concluded that what happens inside reserves is strongly linked to what happens in the surrounding area (Laurance et al., 2012). Experts reported declines in large-seeded old-growth trees and epiphytes, and increases in pioneers and generalists, lianas, and invasive species. Many protected areas fail to prevent overexploitation of valuable plants and/or the animals on which they depend, and many are subject to encroachment by farmers or their fires. Invasive species and air pollution are also not excluded by legally designated boundaries. Moreover, the fragmentation of the protected area system in many countries means that even the more mobile plant species will not be able to track climate change over future decades unless their dispersal agents can cross large intervening areas of agriculture or urban development (Corlett and Westcott, 2013).

The best answer we have currently is to try to preserve large areas of forest (and other habitats, such as natural grasslands) over broad altitudinal gradients in steep topography, which should maximize the ability of plants to respond to climate change by movement. Where this is no longer possible, as will often be the case, it may be possible to use ecological restoration to recreate the missing links between fragments, and/or to make the intervening agricultural areas more wildlife friendly. Where none of these are possible, or in areas where there is no steep topography, vulnerable plant species may need to be moved artificially to cooler (or drier or wetter) areas that they do not currently inhabit (Corlett and Westcott, 2013; Corlett, 2015). Such managed translocation (or assisted migration) is, rightly, controversial, but alternative options are limited.

To be effective, *in situ* conservation requires species-level monitoring to ensure that viable plant populations of threatened species persist within protected areas. If declines are detected, appropriate interventions, such as habitat management, invasive species control, prevention of overexploitation, and/or managed translocation to a new site, can be considered. Ideally, each threatened species would have a separate species management plan (Heywood, 2015). Monitoring the many unknown species in tropical forests is clearly impossible, but changes in status of known species may flag general problems in protected area management that can be reduced, to the benefit of both known and unknown species.

7.4. Controlling overexploitation

Overexploitation, within and outside protected areas, will need additional action. Controlling subsistence use runs into practical and moral issues, but most damage is caused by collection for markets, often by professional collectors. Many countries have laws against this which are inadequately enforced, but often commercial collection makes use of legal loopholes which need to be closed. The CITES convention (Convention on International Trade in Endangered Species of Wild Flora and Fauna) can be effective in limiting transboundary trade in plant species (Sharrock et al., 2014), but for many species the major markets are internal and in this case enforcement depends on overworked police forces without relevant training and with many higher priorities.

7.5. Ex situ conservation

Target 8 of the GSPC is the *ex situ* conservation (i.e. outside their natural habitat) of at least 75% of threatened plant species, with at least 20% available for recovery and restoration programs. Most angiosperms (75%–80%; Walters et al., 2013) have ‘orthodox’ seeds that can be dried and then stored at low temperatures for a varying length of time, so this is a potentially attainable target, although we are still far from achieving it. The Millennium Seed Bank in the UK, the world's largest, has a target of storing 25% of the world's plant species by 2020 (www.kew.org/science-conservation/collections/millennium-seed-bank) and several other large seed banks have ambitious targets. Low storage costs mean that it is possible to maintain many genetic individuals of each species and also, where necessary, to keep separate collections of multiple wild populations (Hoban and Schlarbaum, 2014). In practice, however, the quality of collections in seed banks varies, with some suffering from low viability and many failing to represent the genetic diversity of the wild populations.

The situation for the other 20%–25% of species, with ‘recalcitrant’ seeds that cannot be stored under standard conditions is currently far worse. Cryopreservation, usually in or over liquid nitrogen, is currently the only practical means of long-term storage. Storage of whole recalcitrant seeds is rarely possible, but excised embryos, embryonic axes, or dormant buds of many non-tropical and some tropical species have been stored successfully, although protocols often need adjusting for each species (Berjak and Pammenter, 2013). As a result, these techniques are currently used mostly with crop plants and their wild relatives. The majority of wild species with recalcitrant seeds are in the lowland humid tropics, however, where the numbers of threatened species are highest and the resources for conservation least. More research is urgently needed, but as ultra-low temperature freezers become cheaper, avoiding the need to replace liquid nitrogen as it evaporates, cryopreservation is likely to become easier and, hopefully, more widespread.

Currently the simplest *ex situ* conservation strategy for these species is to grow them in ‘living collections’ in botanical gardens, arboreta, and similar facilities. However, growing enough trees to represent the full genetic diversity of a species may require an inordinate amount of space, while living collections of shorter lived species need to be carefully managed to avoid inbreeding, hybridization, or selection for the garden conditions (Ensslin et al., 2015). The use of new molecular techniques for genetic optimization of living collections can help (Wee et al., 2015), but these are not yet widely available where they are most needed. In many botanical gardens and other institutions in the tropics the living collections include many threatened species, but the majority of these are represented by only one or a few genetic individuals, so these collections are of little use for conservation. Economically important timber trees—which are rarely threatened—are usually the only tree species with adequate living collections in the tropics (FAO, 2014). There is an urgent need for botanical gardens to move beyond the ‘stamp-collecting’ mentality to collecting for conservation purposes (Cavender et al., 2015). Networking between gardens in the same climate zone can help with space constraints, as can the ‘safe sites’ approach used by the International Conifer Conservation Programme, based at the Royal Botanical Gardens Edinburgh. These sites include public parks, golf courses, hospitals, and private land owners that grow threatened conifers as part of a coordinated, out-sourced, *ex situ* conservation programme (Cavender et al., 2015). Overall, the *ex situ* conservation of tropical plants continues to be a major gap in global plant conservation and needs to be a major focus of both research and action.

8. Priorities

Despite the daunting global scale of plant conservation needs, a target of ‘zero extinction’ is not implausible at the local level, if *ex situ* facilities are available to fill the gaps in a well-designed protected area system. However, prioritization of threatened species for protection is necessary at a global scale because of the large variation in local conservation capabilities, particularly in the tropics. While a variety of criteria have been suggested for this process, the most obvious ones are: potential economic value (e.g., wild relatives of crop and medicinal plants; Sharrock et al., 2014), ecological importance (i.e., species with key roles in ecosystem functioning), and phylogenetic uniqueness (i.e. species with no close relatives) (Corlett, 2014a). The first two criteria are likely to be most useful at the local level, while phylogenetic distinctiveness makes most sense when setting global priorities. The EDGE (Evolutionarily Distinct and Globally Endangered) program at the Zoological Society of London has drawn conservation attention to many previously neglected animal species and could do the same for plants (www.edgeofexistence.org). EDGE plants are an irreplaceable part of the plant kingdom, each representing millions of years of evolutionary history, and are also likely to have unique ecological roles.

9. Conclusions

There do not need to be any more plant extinctions. The combination of a well-designed, well-monitored, and well-managed system of protected areas, with *ex situ* conservation in seed banks and, where necessary, living collections and cryogenic storage, should be enough to protect all land plant species through the next few decades of rapid global change. The major barriers to this goal of zero global plant extinctions are: the many undescribed plant taxa, which cannot receive targeted protection; the low percentage of known taxa whose status has been assessed, so we cannot efficiently assign protection; the uneven global coverage of protected areas, particularly in the hyperdiverse humid tropics, and the lack of plant inventories within them; the massive underrepresentation of tropical taxa in *ex situ* collections; and the apparent absence of any sense of urgency among everyone from plant biologists to government officials, conservation NGOs, and the general public. None of these problems are inherently intractable and all the gaps could be filled. We know how to do this, but we are not currently doing enough.

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