Trends in
Plant Science

CellPress

Review

Achieving zero extinction for land plants

Richard T. Corlett [1,2,*]

Despite the importance of plants for humans and the threats to their future, plant conservation receives far less support compared with vertebrate conservation. Plants are much cheaper and easier to conserve than are animals, but, although there are no technical reasons why any plant species should become extinct, inadequate funding and the shortage of skilled people has created barriers to their conservation. These barriers include the incomplete inventory, the low proportion of species with conservation status assessments, partial online data accessibility, varied data quality, and insufficient investment in both *in* and *ex situ* conservation. Machine learning, citizen science (CS), and new technologies could mitigate these problems, but we need to set national and global targets of zero plant extinction to attract greater support.

Highlights

Despite the importance of plant diversity to human wellbeing, and the threats to its survival, plant conservation receives far less support compared with vertebrate conservation.

Plants can be conserved *in situ*, in protected areas, and *ex situ*, in living collections, seed banks, or cryogenic storage. At least one option is available for all species that need it, but no single method works for all.

Achieving zero plant extinction requires completion of the plant inventory, status assessment for all known species, digitization of all herbarium specimens with links to other resources in an online global metaherbarium, and separate recovery plans for each threatened species.

The major bottleneck is the shortage of skilled people. New technologies, machine learning, and citizen scientists can extend the reach of experts, but training and incentives are needed to increase their number.

The need for plant conservation

The critical importance of terrestrial plant diversity for human well-being is undisputed. Numerous species are utilized for food, medicine, timber, fiber, and fuel, and many of these uses are species specific [1–3]. Plants also dominate the provision of essential ecosystem services, including carbon fixation, clean water, and erosion control, contribute to the spiritual, cultural, and emotional values of nature, and provide food and shelter to most terrestrial animals. Recent estimates of the proportion of vascular plant species threatened with extinction range from 21% to 44% [4]. The major documented threats are from land-use change and unsustainable harvesting [5], but invasive pests and diseases [6] are a growing problem, and modelling suggests a potentially large additional threat from anthropogenic climate change [7]. Known plant extinctions are so far much fewer than for well-studied animal groups (571 species of seed plants globally over the past 250 years [8]), but this is undoubtedly an underestimate. Much of the planet was transformed before botanical exploration started; thus, there are likely to have been many 'dark extinctions' of species before they were described [9]. The major concern is that the gap between predicted and observed extinctions represents an **extinction debt** (see Glossary) that will be paid over the coming decades and centuries [4].

Actions to reduce threats to natural ecosystems are urgently needed, along with large-scale ecological restoration in areas where these ecosystems have been destroyed or badly degraded. These actions would benefit many threatened plant species [5], but are not the focus of this review. Here, I focus on the species level and the specific actions needed to prevent the predicted extinctions. The target is zero extinction, rather than reduced extinction or some non-zero percentage, for several reasons. First, 'human-induced extinction of known threatened species is halted' is part of Goal A for 2050 in the recently agreed Kunming–Montreal Global Biodiversity Framework[i]. Second, plant conservation is generally much cheaper on a per-species basis compared with the conservation of vertebrates [10]; thus, a greatly increased effort for plants would not add much to current conservation budgets. Moreover, the marginal costs of adding additional species to existing conservation plans are relatively low, particularly for rare species with few populations to protect, since they can often make use of existing protected area systems, *ex situ* facilities and protocols, and expertise. Third, there is evidence that rare species with rare traits may

[1]Center for Integrative Conservation, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Yunnan 666303, China
[2]Center of Conservation Biology, Core Botanical Gardens, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Yunnan 666303, China

*Correspondence:
corlett@xtbg.org.cn;
rtcorlett@gmail.com (R.T. Corlett).

make important contributions to ecosystem functions and increase the resilience of plant communities to future environmental change [11]. Fourth, a simple, ambitious target is needed to attract support for plant conservation. Finally, if zero extinction is potentially achievable for plants, a less ambitious target would be inexcusable.

Therefore, I review recent developments relevant to plant conservation and attempt to answer three general questions: what are the current barriers to successful plant conservation? Is zero extinction of plant species possible? If so, how do we get there?

Barriers to plant conservation

Lack of support

Neither the importance of plant diversity nor the growing threats to its future have translated into a level of funding and other support equivalent to that given to the conservation of vertebrates [10,12]. This massive disparity in support is often attributed to inherent **plant blindness**, but this has been reinforced in recent decades by the erosion of botanical content in education [13]. More effective botanical education and outreach might challenge zoocentrism in conservation [10,12,13].

The incomplete inventory

The current global checklist of vascular plants has ~382 000 accepted species (World Flora Online[ii]) but an estimated 10–25% more are still undescribed [14]. Undescribed species are invisible to science and conservation planning, and spatial variation in completeness of the inventory may result in underestimates of regional diversity and incorrect conservation priorities. Checklists of species at particular sites underpin conservation planning and action. Approximately 2000 additional species are described each year, with the main bottleneck being a shortage of taxonomists, particularly in the tropics, where most undescribed species are expected [14,15]. There are also thousands of species that have been collected and stored in herbaria but not yet identified [16].

Falling sequencing costs facilitate the recognition of new species in the laboratory, from herbarium specimens [17], and, potentially, in the field [18], but the production of a description that is both useful to others and meets the requirements of the International Code of Nomenclature [19] for valid publication is still a time-consuming and highly skilled task. It can also be a thankless task, since users of new plant descriptions either cite no source or cite a data aggregator; thus, no credit accrues to the taxonomist and their institution through citations [20]. Moreover, even when the global checklist is complete, it will be of little use if only taxonomists can identify plants. Another under-rewarded role of taxonomists is enabling the other people involved in plant conservation to accurately identify plants [5], by providing identification services, running training courses and CS activities, and producing Floras, keys, and online guides.

Slow progress in conservation assessment

With 382 000 described plant species, we need a prioritization system to ensure that conservation effort is focused on species under threat. The IUCN Red List of Threatened Species[iii], based on a standard set of criteria, is the gold standard for conservation assessment, but only 15% of plants have been assessed so far at the global level (vs. almost 100% of vertebrates). National and regional assessments cover many additional species, but this coverage is also incomplete, particularly in the tropics [21]. Formal Red List assessment is slow because of the strict data requirements and a shortage of trained assessors, but triage using open-source data and machine learning can focus attention on species needing urgent study (Box 1). Both expert and automated

Glossary

Assisted gene flow: movement of better-adapted genotypes within the native range of a species to assist adaptation in a wild population. The better-adapted genotypes may come from other wild populations or *ex situ* collections.

Citizen scientists: volunteers participating in scientific research (as opposed to professional scientists); also called community scientists to avoid the appearance of assuming citizenship.

Conservation translocations: general term for the movement and release of organisms for conservation reasons, including reintroduction and reinforcement, where organisms are released within their native range, as well as conservation introductions outside this range to avoid extinction or to restore ecological function. The organisms moved may come from *ex situ* collections or wild populations.

Exceptional plants: species that cannot be preserved long-term in conventional seed banks because their seeds are desiccation sensitive, or short-lived under standard seed bank conditions, or hard to collect or germinate.

Extinction debt: expected future extinctions because of events in the past. For example, if habitat fragmentation or degradation leads to failure of regeneration, adult plants may persist for decades or centuries before the species becomes extinct.

Gene drives: genetic mechanisms whereby a particular heritable element biases inheritance in its own favor, resulting in the gene rapidly spreading through the population over successive generations. Gene drives occur naturally, and synthetic gene drives could be used to introduce a desired genetic modification to wild populations.

Georeferencing: process of assigning geographical coordinates to herbarium specimens using information from specimen labels and other sources.

Living collections: collections of growing cultivated plants in botanical gardens or similar institutions. Their main functions are research, display, education, and conservation.

Plant blindness: tendency to ignore plants.

Seed bank: place where seeds are stored long-term under standard conditions (typically at –18°C) after drying.

Box 1. Machine learning in plant discovery, description, and conservation

Machine-learning algorithms build a statistical model based on training data to make predictions about novel data without being explicitly programmed to do so, emulating human expertise for a specific task. Training requires human experts, but the trained model can then repeat the task quickly and tirelessly. Most recent applications of machine learning have been proof-of-concept studies, requiring both botanical and machine-learning expertise; thus, they have not yet made a significant contribution to filling the skills gap, but progress is rapid [25,67]. Automated identification of plant species in the wild is now available on CS platforms, such as iNaturalist[xiii] and Pl@ntNet[xiv] [68], but only for species with many photographs available online. Even in the relatively well-botanized Americas, 40% of vascular plant species have no accessible photographs online [69]. Human experts can use herbarium specimens to help them identify living plants, but transferring learning from flattened, brown specimens to field photographs has not been successful with machine learning so far [16,68]. However, automatic identification of herbarium specimens with models trained on similar specimens has proved to be an easier task, even though these models have not yet used the additional meta-data (date, location, tentative ID, etc.) that are usually available to human experts [16]. Automatic identification could be used to flag potentially mislabeled species in online aggregations of digitized specimens [16]. Also very promising is the use of machine learning in rapid Red List assessments, using either a criteria-based approach based on occurrences, habitat requirements, and remotely sensed data on habitat availability, or a prediction-based approach using existing Red List assessments to train models to predict status from range size, traits, and other species-level information [70–72]. Automation is likely to be most useful for predicting Least Concern status, an estimated 60% of all species, since the requirements for listing are straightforward, mostly available online, and an app is available [62]. Machine learning can also be used directly in the creation of species distribution models (SDMs) using available occurrence records, remote sensing, and other data sources [73].

assessments are limited by the need for an accurate description of the spatial and ecological distribution of each species (i.e., where it occurs and in what habitats). More than one-third of known plant species have five or fewer recorded locations [7]. Modelling can predict additional locations (Box 1), but the bottleneck is still boots on the ground [22]. At least some of these boots can be on the feet of **citizen scientists** (Box 2).

Access to data

The most reliable location records come from herbarium specimens, since their identities can be checked. However, the nearly 400 million herbarium specimens are held in >3500 herbaria in 183 countries [23]; thus, data access is a major bottleneck for conservation assessments. The increasing availability of scanned images and transcribed label data through global [Global Biodiversity Information Facility (GBIF)[iv], Botanical Information and Ecology Network (BIEN)[v]]

Box 2. CS in plant conservation

CS is the participation of volunteers in scientific research. It can extend the reach of professional scientists in space and time cheaply, while building long-term support for plant conservation. However, it is also an additional call on the time of the limited pool of experts, and data quality is often a concern [74]. The use of CS data in published plant science is rare compared with birds, mammals, and the more charismatic invertebrate groups [74–76], but there are enough successful examples [76,77] to show that it is possible, at least with attractive plants that are easily observed from the ground. Such plants are more easily photographed compared with most animals and many accessible plant records come from platforms, such as iNaturalist[xiii], where observers post unstructured, opportunistic observations, including a photograph, date, and coordinates. In December 2022, iNaturalist had >50 million such observations of 140 988 species of plants, of which >29 million records of 114 703 species were 'research grade', meaning the identification was agreed by more than two-thirds of the identifiers[xiii]. Such sites can provide very large numbers of presence records, but lack of information on sampling effort and likely systematic biases in what is recorded [78], limit how these data can be used. Adding structure to data collection and upload can reduce these limitations but raises the entry barrier for participants and reduces their number [78]. Participants in eBird[xv], the most successful global CS scheme, upload complete bird checklists with species abundances and search effort, while butterfly monitoring schemes use fixed transects [79]. Neither approach appears to have been used with plants, but a successful 'Adopt a Plant' CS monitoring scheme in northeast Spain, coordinated by scientists, collects long-term abundance data on local populations of plant species of concern with rigorous, species-specific, sampling protocols [76]. These data can feed directly into conservation planning and management. Local CS monitoring schemes can use expert verification to ensure data quality [77], but large-scale platforms usually use community consensus (crowdsourcing) and/or machine learning (Box 1) for initial identification, with expert verification used only for records that are flagged as needing review [74]. Volunteers can also be of great value during the digitization of historical plant collections, including label transcription, georeferencing, and checking specimen identifications [80].

and regional (e.g., Atlas of Living Australia[vi], Chinese Virtual Herbarium[vii], and Brazil's Reflora program[viii]) data aggregators is transforming access, but there is still a huge backlog of inaccessible specimens. Moreover, not all specimens provide useable data, since older specimens often lack accurate location information and **georeferencing** from handwritten labels in multiple, idiosyncratic styles is skilled and labor-intensive [24].

Ideally, data from herbarium specimens will be linked in a 'global metaherbarium' [25] to other relevant digital resources, including other physical preparations, molecular sequences, maps, status assessments, photographs (including photomicrographs of key characters), trait data, habitats, and uses [25,26]. Moreover, much of the value of plants to humans depends on species-specific information contained in indigenous and local knowledge, some held in threatened languages [27]. Recording this and linking it to scientific databases should be a priority, despite the additional challenges of dealing with different knowledge systems. In addition, while retroactive digitization and networking of existing herbarium collections are crucial, we need to rethink the process of plant collection and preservation so that new collections are part of 'extended specimen networks' from the beginning [25,26].

Data quality

Online accessibility of high data volumes to nonexperts through data aggregators puts a premium on data quality since most users cannot check this themselves. Incorrect data can lead to wrong conservation actions. Specimens are often wrongly identified, particularly in tropical herbaria rarely visited by experts [28], and location data may be incorrect or wrongly transcribed [24,29]. Taxonomic changes mean the same taxon may appear under multiple names, or multiple taxa appear under the same name, although, fortunately, disagreements on the delineation of plant species are rare [30]. Initial checking of online images can be automated using machine learning to flag potential problems (Box 1), but the final check needs a human expert on that particular group [29]. Combining automated identification of photographs (much easier for living plants than for flat, brown, herbarium specimens) with expert checking can make it possible to use CS location data in conservation assessments (Box 2). Even when all the data used are error free, spatial variation in the extent of data completeness can result in errors in the identification of diversity hotspots [31].

Conservation in practice

Conservation of what?

Most data are available at the species level, but the species recognized by taxonomists are often not the most appropriate level for the conservation of plants. The increasing availability of genomic information has shown that plant species are often not the discrete entities recognized in classical taxonomy, with both significant gene flow between related species and significant barriers within species common. Local adaptation of plant populations to climate, soil, and other factors is also common [32]; thus, multiple separate populations will often need to be protected to conserve the full potential of the species [33]. This is standard practice with crop and forestry species, and their wild relatives, but less common with other wild species [34]. Even species rated as Least Concern, because they are at no risk of extinction, may be losing genetic diversity [33]. The robust detection of local adaptation requires reciprocal common garden trials and/or intensive genomic studies; thus, in practice, conservation efforts should target populations from across the full morphological, geographical, and ecological range of the species [35,36]. Alternatively, if genetic data are available, conservation may aim to maximize the overall genetic diversity and representativeness of collections to maximize the adaptive potential in the face of global change [33]. However, spatial genetic structure detected with neutral markers does not necessarily represent local adaptation, and targets based on the percentage of *in situ* alleles conserved (e.g., 95% [37]) do not distinguish between adaptive, neutral, and deleterious variation, although a 'save as much as possible' strategy may be the best we can do at present. When there are fuzzy species boundaries, there is a risk that both the taxonomy and, as a consequence, conservation strategies emphasize clear-cut differences and neglect phenotypic intermediates and outliers [36]. We may also need to consider epigenetic variation in some circumstances [38], but this remains an open question.

Conservation *in situ*

Conservation of self-sustaining wild populations in protected areas (*in situ*) is the ideal, since it allows continued evolution in response to ongoing environmental change (such as climate change, and new pests and diseases) and the continued support of mutualists, herbivores, and pathogens, some of which may face extinction without their only plant hosts. However, most existing protected areas were established to protect charismatic landscapes or vertebrates [39]; thus, they often provide inadequate coverage of threatened plant taxa. The Important Plant Areas (IPA) program[ix], which identifies areas with threatened plant species or vegetation types, and/or exceptional plant richness, aims to counteract this bias, but so far only covers a minority of countries [5]. The establishment of new protected areas has costs, including foregone alternative land uses, which are borne disproportionately by poorer communities and nations [40], but 'microreserves' (<50 ha) can be effective for narrow endemics and isolated populations while minimizing these costs [41].

It is important to recognize that the recorded presence of a plant species within a protected area is not evidence for effective conservation of that species [42,43]. Conservation requires that a viable population persists over time or that a previously nonviable population recovers. At minimum, this will require long-term monitoring and, in many cases, it will also need *in situ* management interventions (Box 3).

Conservation *ex situ*

Ex situ conservation is needed as back-up for wild populations under continued threat, and to provide material for research, public education, and recovery activities [44]. Almost one-third of plant species are growing in botanical gardens, mostly in the temperate zone, but most of these are represented by only a few individuals. Coordination between gardens permits larger, more

Box 3. Species recovery plans

A threatened species in IUCN terminology is one that is 'considered to be facing a high risk of extinction in the wild'[ii]; thus, all plant species assessed as threatened require conservation action for long-term survival. A species recovery plan (and various similar names) describes the status, threats, and conservation actions required for the recovery of a threatened species to a state where it can maintain itself [42]. In some cases, groups of co-occurring species face similar threats and require similar actions, but initial status assessments and subsequent long-term monitoring need to be done at the individual species level. Recovery plans may also be needed for threatened populations of nonthreatened species if these are genetically distinct [81] or of national concern [21]. Plans for individual populations and species then need to be integrated with area-based conservation actions [42]. Clearly, however, it is impossible to produce recovery plans for the many undescribed species and it is difficult for species without a conservation status assessment [43].

Species recovery plans should be based on a detailed threat analysis and understanding of the biology of the species [42,81]. The aim is to identify the ecological factors limiting persistence and recovery of the population. This may require additional, targeted research on species ecology and genetics [81]. Conservation actions to mitigate the identified threats may then include both local interventions and broader threat mitigation on a landscape or regional scale. *In situ* interventions may include, as appropriate, habitat protection, enhancement, and restoration, fire management, herbivore management, and weed, pest, and disease control [81]. Translocation has been widely used to mitigate development threats, but these actions are poorly documented and few result in self-sustaining new populations [82]. Appropriate *ex situ* back-up is part of most plans, and reintroduction or reinforcement may also be included. Actions need to be coordinated across relevant institutions, but with a single lead institution accountable for the results [42]. Monitoring is essential throughout the recovery process and should include population sizes and trends to anticipate extinction risk [76]. The IUCN recently launched a new tool (IUCN Green Status of Species assessments) for measuring species recovery and assessing the impacts of conservation actions [83].

representative **living collections**, although management costs and space requirements limit how many species can be covered. Few living collections are genetically representative of the wild populations and almost all have a 'genetic conservation gap' between the amount of genetic diversity that could have been captured, if the individuals had been selected with an ideal sampling design, and the amount actually captured [37]. A variety of public and private green spaces could provide a lot of additional space for living collections, but such 'urban conservation gardening' would be a significant additional management challenge [45]. Another problem with living collections is that growing plants may also be subject to unintentional selection for survival in cultivation, inbreeding, and genetic drift as a result of small population sizes, and hybridization and introgression if grown with related taxa, especially when cultivated for multiple generations [46].

The seeds of most plant species can be stored for many years under standard conditions (drying to 15% relative humidity at 15°C and freezing at –18°C) in **seed banks**, allowing numerous genetic individuals to be conserved cheaply in a small space. More than 17% of seed plant species are represented in seed banks [47], but there is wide variation in seed longevity under these conditions, with some species considered 'orthodox', because they can be successfully dried and frozen, surviving only a few years [48]. This is expected to be a particular problem for tropical taxa. In addition, around 10% of species have 'recalcitrant', desiccation-sensitive seeds that cannot be dried and frozen. This includes many trees from humid tropical forests. Plant species with seeds that are short-lived in conventional seed banks (half-life <20 years), desiccation sensitive, unavailable, or just exceptionally difficult to germinate (around 20% of all plants) have recently been branded as **exceptional plants** [49] to make them more visible to researchers, managers, and funders.

Cryogenic storage techniques for various tissues, usually in or over liquid nitrogen, but potentially in ultra-low temperature refrigerators, have been developed for many of these species and appear to be technically possible for all, but no single method works for every species tested [49,50]. Short-lived orthodox seeds can often be frozen directly, and cryopreservation of zygotic embryos or embryonic axes is possible for some desiccation-sensitive species. Shoot tips are the most widely used somatic tissues, but are less easy to regenerate to growing plants. Most existing cryobanks focus on economic species [44], but a new Exceptional Plant Conservation Network[x] aims to share knowledge and experience, and encourage a more systematic approach to protecting all endangered exceptional species [49]. Most of the cost is associated with developing protocols for each species, while maintenance costs for cryopreserved material are low [50]. At present, however, large-scale cryobanking in the tropics, where it is most needed [51], is likely to be limited both by the cost and the technology.

The difficulties of dealing with wild species *ex situ* raise an obvious question: why not just save genomic sequence data [44]? A single, high-quality, plant genome sequence conserves much of the information in a growing plant. A pan-genome, representing the entire set of genes within a species, would be even better. We cannot currently regenerate genomes into individual plants, but using sequence data from an extinct species to edit the genome of an extant relative may eventually be feasible [52]. This would be a last resort, since the de-extinct species would have lost all genetic diversity and any specialist associates (Box 4), but it suggests that highly endangered species should have priority in global plans for sequencing all plant genomes.

A major justification for *ex situ* collections is that they allow a species to be used in conservation activities. Where sufficient propagules are available, threatened plant species can be included in habitat restoration projects. These projects can contribute to biotic homogenization by favoring species that are cheap and easy to propagate, but can also, with care, make a large contribution to rare plant conservation [53]. **Conservation translocations** of single species are also

Box 4. The problem of associated species

Wild plants are members of networks linking numerous species of plants, animals, and microbes, including competitors, pathogens, herbivores, and mutualists, with relationships ranging from generalist to specialist. These relationships are a major reason for favoring conservation *in situ*, and the continued presence of mutualists may be necessary for the long-term persistence of wild plant populations [84,85]. Plants *ex situ* are stripped of most associated species, although living collections within the native range attract a subset. Indeed, any living plant material may carry associated fungi, bacteria, or viruses [44]. These may be beneficial, neutral, or harmful, and the risk of moving pathogens internationally complicates management of *ex situ* collections.

The need to conserve beneficial microbial associates so that plants from *ex situ* collections can be re-introduced to areas from which they have been lost, or introduced to areas where they never occurred, has received less attention, except for orchids. Orchid seeds lack endosperm and depend on fungi for germination and establishment, and sometimes in mature plants [84]. In some, this is a specialized relationship and establishment in the wild may be difficult or impossible without the correct fungus. Mycorrhizal fungi can be kept *ex situ* as growing cultures or in cryostorage [86]. Inoculation with specific strains of rhizobial bacteria is common in agriculture, but it is not clear whether this will be necessary for re-establishing wild legumes [87]. Orchids and legumes are the second and third largest plant families, respectively, and reliance on microbial symbionts is known in several others. Moreover, there is evidence that elements of the local microbiome can improve growth in other plants [88].

Specialized pollination is also common in orchids [84] and some other families. Obligatory relationships, where plant and pollinator are wholly dependent on each other, are known in many figs (*Ficus*, Moraceae) and a few other genera [89]. In these cases, conservation *in* or *ex situ* (but within range) of enough growing plants to maintain a population of pollinators is the only option. Seed dispersal is less specialized, but Pleistocene megafaunal extinctions and recent defaunation of tropical forests have greatly reduced dispersal of large fruits and seeds [85], with potential long-term implications for conservation. Co-extinctions following the loss of wild populations of plant species are most likely in herbivores and pathogens, since plant defenses select for specialization [90], but this has received little attention, despite the potential for hundreds of thousands of additional extinctions [91].

increasing (Box 3). However, reintroductions of plants from *ex situ* collections to parts of their native range from which they have been eliminated are still fairly rare, and their long-term success cannot yet be evaluated [54]. The use of *ex situ* collections to reinforce declining wild populations is even less common, although preventing extinction in the wild is always preferable to reversing it, since it preserves interactions lost in captivity (Box 4). Release of better-adapted *ex situ* genotypes within the native range to assist adaptation in a wild population **(assisted gene flow)** is another option [55]. In the face of intractable threats, such as new diseases or novel climates, hybridization with better-adapted relatives or targeted genetic intervention to promote traits that aid survival might be justified as an alternative to extinction in the wild [56,57], although the potential use of **gene drives** to push genetic modifications through extant wild populations is controversial [58].

Integrated conservation

Unless a species has multiple secure populations in the wild, an integrated conservation program involving both *in* and *ex situ* approaches will be necessary, based on an individual species recovery plan (Box 3). *In situ* conservation is always preferred where possible, but *ex situ* back-up is needed for all species or significant populations that are threatened in the wild. Space-limited living collections will usually need to be supplemented by more genetically representative collections in seed banks or cryobanks [51,59]. However, for species with seeds that cannot be stored in conventional seed banks, and for which cryobanking is currently unavailable, these living collections and the horticultural skills available in botanical gardens are still the ultimate back-up [44].

Concluding remarks

This review supports previous statements that there is no technical reason why any known plant species should go extinct [49–51,60,61]. There are many problems, but also potential solutions for most of them (Table 1, Key table). Future extinctions of known species will most likely reflect the shortage of skilled people, a consequence in turn of the inadequate long-term funding and

Outstanding questions

How great a threat is anthropogenic climate change to global plant diversity? Are the predictions from current modelling approaches accurate?

When will I be able to identify any plant anywhere with a handheld device and how will it be done?

Can cryogenic storage of plant tissues be made as quick and easy as conventional seed banking? This would require one or a few standard protocols that can be applied to the majority of species. Is this possible?

How can current ambitious plans for habitat restoration worldwide contribute to the conservation of threatened plant species?

How can we make plant discovery and description an attractive career option for young people?

What proportion of threatened plant species requires specific microbes, pollinators, seed dispersal agents, and/or other associates to successfully establish new populations in the wild? Can we maintain these associates *ex situ*? Conversely, how many specialist pests and pathogens are at risk from extinctions of their plant hosts in the wild and can we maintain them *ex situ*?

Key table

Table 1. Key problems and potential solutions for plant conservation

Problem	Potential solutions	Refs
Incomplete inventory	Train more taxonomists; incentivize plant discovery and description; use rapid sequencing in field	[18,20,63]
Slow progress in global conservation status assessment	Train more assessors; use national-level assessments of endemics; automate rapid assessments with machine learning; use CS to increase location records (Box 2)	[21,62,70–72,74]
Access to data	Digitize all herbarium specimens; create an online global meta-herbarium and extended specimen network	[25,26,80]
Data quality	Support taxonomists in biodiversity hotspots; use machine learning to check identifications (Box 1)	[16,63]
Conservation below species level	Conserve populations across full geographical and ecological range of species; use genetic and genomic data if available	[33–37]
Inadequate coverage of threatened plants in protected areas	Identify and protect Important Plant Areas[ix]; establish plant microreserves	[5,41]
Low size, genetic diversity, and representativeness of living collections	Coordinate botanical gardens; plant in public green spaces; make additional collections from the wild; supplement with seed banks and cryobanks	[35–37,45–47]
Limitations of seed banking	Develop cryopreservation protocols; network to share experience and fill gaps in coverage; back up with living collections	[49–51]
Effective integration of conservation actions	Prepare individual species recovery plans (Box 3)	[42,43,59,81]
Conservation of associated species	Do more research (Box 4); cryopreserve important microbial associates; manage living collections to preserve specialist associates	[84,86,87]
Lack of support	Set zero plant extinction targets at local, national, and global levels; improve public and formal education; prioritize national endemics	[13,61,66]

other support for plant conservation. This has resulted in a patchy and ad hoc implementation of conservation actions that leaves most threatened species unmonitored and unprotected. There are some major areas that need more research, including practical cryobanking [44,51] and the wider use of threatened species in ecological restoration [53], but most of what is needed is not novelty but a lot more of the same: more people, more space, more funding, more monitoring, and more of the local interventions that work (Box 3). The low proportion of plant species formally assessed for conservation status in the IUCN Red List[iii] currently constrains all conservation planning and action [5], but accepting national-level assessments of single-country endemics as global assessments [21] and accepting automatic assessments (Box 1) for Least Concern status [62] will help alleviate this.

The incomplete inventory and the fate of the unknown species that have not yet been described is a separate problem, although the same institutions and people are involved. The colonial legacies that have separated the major collections from the plant-rich regions that supplied them need to be acknowledged and mitigated [25]. Targeted collections in areas where more species are expected are a priority, as is the training of more taxonomists from these countries [63]. Plant collectors and taxonomists in undercollected regions are botanical heroes and deserve to be treated as such. There must be incentives that encourage people to put their time and effort into plant discovery and description, rather than career-advancing alternative activities, and consistent long-term funding so that more young people are encouraged to take up this critical task as a career. Few people in recent decades have become professors by describing new species.

Major successes in plant conservation over the past decade have come from a combination of global consortia, taking an inclusive, top-down approach, and species-level action by conservationists on the ground. Botanic Gardens Conservation International (BGCI)'s Global Conservation Consortia[xi] aim to coordinate conservation action for particular plant groups, including, so far, *Acer*, cycads, dipterocarps, *Erica*, *Magnolia*, *Nothofagus*, *Quercus*, and *Rhododendron*, in which multiple botanical gardens have an interest [64], while the Global Tree Assessment aims to complete conservation assessments of all the world's ~60 000 tree species[xii]. The global checklist produced by the World Flora Online consortium [65][ii], linked with the other digital resources in the extended specimen network [25,26], could provide the basis for extending this approach to the entire global vascular plant flora. However, to attract the funding and other support that such an ambitious project requires, we need a clear target. A global target of zero plant extinction may seem like a remote aspiration, but local, regional, and some national zero extinction targets are potentially achievable now and would provide the incentives needed to fill gaps in our current knowledge and capabilities (see Outstanding questions). National targets make particular sense, because a large majority of endangered species are national endemics and prioritizing the conservation of species that are each country's sole responsibility is more likely to attract public and political support compared with seemingly remote global targets [66].

Acknowledgments

I am grateful to Charles Cannon, Jin Chen, Brian J. Enquist, Keping Ma, Hugh T.W. Tan, Yun-Hong Tan, Kyle Tomlinson, and an anonymous reviewer for useful discussions, comments, and suggestions.

Declaration of interests

No interests are declared.

Resources

[i]www.cbd.int/article/cop15-final-text-kunming-montreal-gbf-221222

[ii]http://worldfloraonline.org

[iii]www.iucnredlist.org/en

[iv]www.gbif.org

[v]https://bien.nceas.ucsb.edu/bien/

[vi]www.ala.org.au/

[vii]www.cvh.ac.cn/

[viii]http://reflora.jbrj.gov.br/reflora/PrincipalUC/PrincipalUC.do

[ix]www.plantlife.org.uk/international/important-plant-areas-international

[x]https://cincinnatizoo.org/exceptional-plant-conservation-network-directory/

[xi]www.globalconservationconsortia.org/

[xii]www.bgci.org/our-work/networks/gta/

[xiii]www.inaturalist.org

[xiv]https://plantnet.org/en/

[xv]https://ebird.org/home

References

1. Antonelli, A. *et al.* (2019) Unlocking the properties of plants and fungi for sustainable development. *Nat. Plants* 5, 1100–1102
2. Brink, S.C. (2021) 25 years of Trends in Plant Science: we should all be plant worshippers. *Trends Plant Sci.* 26, 527–529
3. Cantwell-Jones, A. *et al.* (2022) Global plant diversity as a reservoir of micronutrients for humanity. *Nat. Plants* 8, 225–232
4. Nic Lughadha, E. *et al.* (2020) Extinction risk and threats to plants and fungi. *Plants People Planet* 2, 389–408

5. Sharrock, S. (2020) *A Review of Progress in Implementation of the Global Strategy for Plant Conservation 2011–2020*, Secretariat of the Convention on Biological Diversity and Botanic Gardens Conservation International
6. Fensham, R.J. and Radford-Smith, J. (2021) Unprecedented extinction of tree species by fungal disease. *Biol. Conserv.* 261, 109276
7. Enquist, B.J. *et al.* (2019) The commonness of rarity: global and future distribution of rarity across land plants. *Sci. Adv.* 5, eaaz0414
8. Humphreys, A.M. *et al.* (2021) Reply to: Regional records improve data quality in determining plant extinction rates. *Nat. Ecol. Evol.* 4, 515–516
9. Boehm, M.M.A. and Cronk, Q.C.B. (2021) Dark extinction: the problem of unknown historical extinctions. *Biol. Lett.* 17, 2021007
10. Gordon, R.E. *et al.* (2020) Relative costs of conserving threatened species across taxonomic groups. *Conserv. Biol.* 34, 276–281
11. Dee, L.E. *et al.* (2019) When do ecosystem services depend on rare species? *Trends Ecol. Evol.* 34, 746–758
12. Balding, M. and Williams, K.J.H. (2016) Plant blindness and the implications for plant conservation. *Conserv. Biol.* 30, 1192–1199
13. Stroud, S. *et al.* (2022) The botanical education extinction and the fall of plant awareness. *Ecol. Evol.* 12, e9019
14. Cheek, M. *et al.* (2020) New scientific discoveries: plants and fungi. *Plants People Planet* 2, 371–388
15. Gatti, R.C. *et al.* (2022) The number of tree species on Earth. *Proc. Natl. Acad. Sci. U. S. A.* 119, e2115329119
16. Hussein, B.R. *et al.* (2022) Applications of computer vision and machine learning techniques for digitized herbarium specimens: a systematic literature review. *Ecol. Inform.* 69, 101641
17. Kates, H.R. *et al.* (2021) The effects of herbarium specimen characteristics on short–read NGS sequencing success in nearly 8000 specimens: old, degraded samples have lower DNA yields but consistent sequencing success. *Front. Plant Sci.* 12, 669064
18. Pomerantz, A. *et al.* (2022) Rapid in situ identification of biological specimens via DNA amplicon sequencing using miniaturized laboratory equipment. *Nat. Protoc.* 17, 1415–1443
19. Turland, N.J. *et al.* (2018) *International Code of Nomenclature for Algae, Fungi, and Plants (Shenzhen Code) adopted by the Nineteenth International Botanical Congress Shenzhen, China, July 2017*, Koeltz
20. Zeppelini, D. *et al.* (2021) The dilemma of self-citation in taxonomy. *Nat. Ecol. Evol.* 5, 2
21. Holz, H. *et al.* (2022) Assessing extinction risk across the geographic ranges of plant species in Europe. *Plants People Planet* 4, 303–311
22. Hochkirch, A. *et al.* (2021) A strategy for the next decade to address data deficiency in neglected biodiversity. *Conserv. Biol.* 35, 502–509
23. Thiers, B.M. (2022) *The World's Herbaria 2021: A Summary Report based on Data from Index Herbariorum*, New York Botanical Garden
24. Marcer, A. *et al.* (2021) Quality issues in georeferencing: from physical collections to digital data repositories for ecological research. *Divers. Distrib.* 27, 564–567
25. Davis, C.C. (2023) The herbarium of the future. *Trends Ecol. Evol.* 38, 412–423
26. Lendemer, J. *et al.* (2020) The extended specimen network: a strategy to enhance US biodiversity collections, promote research and education. *BioScience* 70, 23–30
27. Cámara-Leret, R. and Bascompte, J. (2022) Language extinction triggers the loss of unique medicinal knowledge. *Proc. Natl. Acad. Sci. U. S. A.* 118, e2103683118
28. Goodwin, Z.A. *et al.* (2015) Widespread mistaken identity in tropical plant collections. *Curr. Biol.* 25, R1066–R1067
29. Oleas, N.H. *et al.* (2019) Muddy boots beget wisdom: implications for rare or endangered plant species distribution models. *Diversity* 11, 10
30. Govaerts, R. *et al.* (2021) The World Checklist of Vascular Plants, a continuously updated resource for exploring global plant diversity. *Sci. Data* 8, 215
31. Qian, H. *et al.* (2022) Global patterns of fern species diversity: an evaluation of fern data in GBIF. *Plant Divers.* 44, 135–140
32. Leimu, R. and Fischer, M. (2008) A meta-analysis of local adaptation in plants. *PLoS ONE* 3, e4010
33. Exposito-Alonso, M. *et al.* (2022) Genetic diversity loss in the Anthropocene. *Science* 377, 1431–1435
34. Pearce, T.R. *et al.* (2020) International collaboration between collections-based institutes for halting biodiversity loss and unlocking the useful properties of plants and fungi. *Plants People Planet* 2, 515–534
35. Zumwalde, B.A. *et al.* (2022) Assessing ex situ genetic and ecogeographic conservation in a threatened but widespread oak after range-wide collecting effort. *Evol. Appl.* 15, 1002–1017
36. Wu, Y. *et al.* (2023) Improving species delimitation for effective conservation: a case study in the endemic maple-leaf oak (*Quercus acerifolia*). *New Phytol.* Published online January 27, 2023. https://doi.org/10.1111/nph.18777
37. Hoban, S. *et al.* (2020) Taxonomic similarity does not predict necessary sample size for *ex situ* conservation: a comparison among five genera. *Proc. R. Soc. B Biol. Sci.* 287, 20200102
38. Rey, O. *et al.* (2020) Linking epigenetics and biological conservation: towards a conservation epigenetics perspective. *Funct. Ecol.* 34, 414–427
39. Delso, Á. *et al.* (2020) Protected area networks do not represent unseen biodiversity. *Sci. Rep.* 11, 12275
40. Green, J.M.H. *et al.* (2018) Local costs of conservation exceed those borne by the global majority. *Glob. Ecol. Conserv.* 14, e00385
41. Fos, S. *et al.* (2017) Plant micro-reserves in Valencia (E. Spain): a model to preserve threatened flora in China. *Plant Divers.* 39, 383–389
42. Heywood, V.H. (2019) Conserving plants within and beyond protected areas – still problematic and future uncertain. *Plant Divers.* 41, 36–49
43. Bolam, F.C. *et al.* (2022) Over half of threatened species require targeted recovery actions to avert human-induced extinction. *Front. Ecol. Environ.* 21, 64–70
44. Breman, E. *et al.* (2021) Plant diversity conservation challenges and prospects—the perspective of botanic gardens and the Millennium Seed Bank. *Plants* 10, 2371
45. Segar, J. *et al.* (2022) Urban conservation gardening in the decade of restoration. *Nat. Sustain.* 5, 649–656
46. Ensslin, A. *et al.* (2023) Does the reduction of seed dormancy during ex situ cultivation affect the germination and establishment of plants reintroduced into the wild? *J. Appl. Ecol.* 60, 685–695
47. Paton, A. *et al.* (2020) Plant and fungal collections: current status, future perspectives. *Plants People Planet* 2, 499–514
48. Chau, M.M. *et al.* (2019) Seed freeze sensitivity and ex situ longevity of 295 species in the native Hawaiian flora. *Am. J. Bot.* 106, 1248–1270
49. Pence, V.C. *et al.* (2022) Defining exceptional species—a conceptual framework to expand and advance ex situ conservation of plant diversity beyond conventional seed banking. *Biol. Conserv.* 266, 109440
50. Funnekotter, B. *et al.* (2021) Cryopreservation. In *Plant Germplasm Conservation in Australia: Strategies and Guidelines for Developing, Managing and Utilising Ex Situ Collections* (3rd edn) (Martyn Yelson, A.J. *et al.*, eds), pp. 307–341, Australian Network for Plant Conservation
51. Pence, V.C. and Bruns, E.B. (2022) The tip of the iceberg: cryopreservation needs for meeting the challenge of exceptional plant conservation. *Plants* 11, 1528
52. Schlebusch, C.M. (2022) Genomics: testing the limits of de-extinction. *Curr. Biol.* 32, R311–R333
53. Holl, K.D. *et al.* (2022) Overcoming biotic homogenization in ecological restoration. *Trends Ecol. Evol.* 37, P777–P788
54. Abeli, T. *et al.* (2020) Ex situ collections and their potential for the restoration of extinct plants. *Conserv. Biol.* 34, 303–313
55. Borrell, J.S. *et al.* (2020) Genomic assessment of local adaptation in dwarf birch to inform assisted gene flow. *Evol. Appl.* 13, 61–175
56. Charles, K.M. and Stehlik, I. (2021) Assisted species migration and hybridization to conserve cold-adapted plants under climate change. *Conserv. Biol.* 35, 559–566

57. Kosch, T.A. *et al.* (2022) Genetic approaches for increasing fitness in endangered species. *Trends Ecol. Evol.* 37, P332–P345
58. Barrett, L.G. *et al.* (2019) Gene drives in plants: opportunities and challenges for weed control and engineered resilience. *Proc. R. Soc. B Biol. Sci.* 286, 20191515
59. Martyn Yelson, A.J. *et al.*, eds (2021) *Plant Germplasm Conservation in Australia: Strategies and Guidelines for Developing, Managing and Utilising Ex Situ Collections*, (3rd edn) Australian Network for Plant Conservation
60. Mounce, R. *et al.* (2017) Ex situ conservation of plant diversity in the world's botanic gardens. *Nat. Plants* 3, 795–802
61. The Organizing Committee of the Fourth International Xishuangbanna Symposium (2019) The Xishuangbanna declaration on plant conservation. *Mol. Plant* 12, 125–126
62. Bachman, S. *et al.* (2020) Rapid Least Concern: towards automating Red List assessments. *Biodiv. Data J.* 8, e7018
63. Pimm, S.L. (2021) What we need to know to prevent a mass extinction of plant species. *Plants People Planet* 3, 7–15
64. Pirie, M.D. (2022) Preventing species extinctions: a global conservation consortium for *Erica*. *Plants People Planet* 4, 335–344
65. WFO Team (2021) World Flora Online gets a new look, a major data update, and launches the WFO plant list. *Taxon* 70, 1415–1419
66. Kraus, D. *et al.* (2023) Prioritizing nationally endemic species for conservation. *Conserv. Sci. Pract.* 5, e12845
67. Harfouche, A.L. *et al.* (2022) A primer on artificial intelligence in plant digital phenomics: embarking on the data to insights journey. *Trends Plant Sci.* 28, 154–184
68. Hart, A.G. *et al.* (2023) Assessing the accuracy of free automated plant identification applications. *People Nat.* Published online February 27, 2023. https://doi.org/10.1002/pan3.10460
69. Pitman, N.C.A. *et al.* (2021) Identifying gaps in the photographic record of the vascular plant flora of the Americas. *Nat. Plants* 7, 1010–1014
70. Bellot, S. *et al.* (2022) The likely extinction of hundreds of palm species threatens their contributions to people and ecosystems. *Nat. Ecol. Evol.* 6, 1710–1722
71. Zizka, A. *et al.* (2021) Automated conservation assessment of the orchid family with deep learning. *Conserv. Biol.* 35, 897–908
72. Walker, B.E. *et al.* (2023) Evidence-based guidelines for automated conservation assessments of plants species. *Conserv. Biol.* 37, e13992
73. Deneu, B. *et al.* (2022) Very high resolution species distribution modeling based on remote sensing imagery: how to capture fine-grained and large-scale vegetation ecology with convolutional neural networks? *Front. Plant Sci.* 13, 839279
74. Baker, E. *et al.* (2021) The verification of ecological citizen science data: current approaches and future possibilities. *Biodivers. Inf. Sci. Stand.* 5, e75506
75. Feldman, M.J. *et al.* (2021) Trends and gaps in the use of citizen science derived data as input for species distribution models: a quantitative review. *PLoS ONE* 16, e0234587
76. García, M.B. (2021) Detecting early-warning signals of concern in plant populations with a Citizen Science network. Are threatened and other priority species for conservation performing worse? *J. Appl. Ecol.* 58, 1388–1398
77. Marcenò, C. *et al.* (2021) Facebook groups as citizen science tools for plant species monitoring. *J. Appl. Ecol.* 58, 2018–2028
78. Di Cecco, G.J. *et al.* (2021) Observing the observers: how participants contribute data to iNaturalist and implications for biodiversity science. *BioScience* 71, 1179–1188
79. Kühn, E. *et al.* (2022) The benefits of counting butterflies: recommendations for a successful citizen science project. *Ecol. Soc.* 27, 38
80. Hedrick, B.P. *et al.* (2020) Digitization and the future of natural history collections. *BioScience* 70, 243–251
81. Monks, L. *et al.* (2019) Recovery of threatened plant species and their habitats in the biodiversity hotspot of the Southwest Australian Floristic Region. *Plant Divers.* 41, 59–74
82. Silcock, J.L. *et al.* (2019) Threatened plant translocation in Australia: a review. *Biol. Conserv.* 236, 211–222
83. IUCN (2021) *IUCN Green Status of Species: A Global Standard for Measuring Species Recovery and Assessing Conservation Impact, Version 2.0*, IUCN
84. Phillips, R.D. *et al.* (2020) Orchid conservation: from theory to practice. *Ann. Bot.* 126, 345–362
85. McConkey, K.R. *et al.* (2022) Megafruit and megafauna diversity are positively associated, while megafruit traits are related to abiotic factors, in tropical Asia. *Glob. Ecol. Biogeogr.* 31, 740–752
86. Reiter, N. *et al.* (2021) Isolation, propagation and storage of orchid mycorrhiza and legume rhizobia. In *Plant Germplasm Conservation in Australia: Strategies and Guidelines for Developing, Managing and Utilising Ex Situ Collections* (3rd edn) (Martyn Yelson, A.J. *et al.*, eds), pp. 373–402, Australian Network for Plant Conservation
87. Pulido-Suárez, L. *et al.* (2021) Applying agronomic principles of rhizobial inoculation to the conservation of a keystone legume species in a high mountain ecosystem on an oceanic island. *Front. Agron.* 3, 660574
88. Koziol, L. *et al.* (2022) Manipulating plant microbiomes in the field: native mycorrhizae advance plant succession and improve native plant restoration. *J. Appl. Ecol.* 59, 1976–1985
89. Yu, H. *et al.* (2021) More examples of breakdown of the 1:1 partner specificity between figs and fig wasps. *Bot. Stud.* 62, 15
90. Maia, K.P. *et al.* (2021) Interaction generalisation and demographic feedbacks drive the resilience of plant–insect networks to extinctions. *J. Anim. Ecol.* 90, 2109–2121
91. Ozman-Sullivan, S.K. and Sullivan, G.T. (2023) Coextinction is magnifying the current extinction crisis, as illustrated by the eriophyoid mites and their host plants. *Acarologia* 63, 169–179