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Opinion

Botanical Monography in the Anthropocene

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Unprecedented changes in the Earth's biota are prompting urgent efforts to describe and conserve plant diversity. For centuries, botanical monographs — comprehensive systematic treatments of a family or genus — have been the gold standard for disseminating scientific information to accelerate research. The lack of a monograph compounds the risk that undiscovered species become extinct before they can be studied and conserved. Progress towards estimating the Tree of Life and digital information resources now bring even the most ambitious monographs within reach. Here, we recommend best practices to complete monographs urgently, especially for tropical plant groups under imminent threat or with expected socioeconomic benefits. We also highlight the renewed relevance and potential impact of monographies for the understanding, sustainable use, and conservation of biodiversity.

Highlights

Botanical monographs have been the gold standard for communicating comprehensive systematic information about plants for over 300 years.

Monographs catalyse species discovery, biodiversity documentation and conservation, and facilitate downstream research on wild and cultivated plant species.

Increased availability of DNA sequence data and digitised resources now provide powerful resources for a new phase of collaborative efforts in monography, focussed on tackling the largest, most threatened, ecologically important, and economically valuable plant groups in an efficient manner.

The Purpose of Botanical Monographs

The Anthropocene [1] has already witnessed unprecedented biodiversity loss as a direct consequence of human impacts [2], prompting calls for coordinated responses to the complex interlinked planetary crises affecting biodiversity, climate change [3,4], and health[i]. Amid alarmingly high rates of species invasions [5], **range shifts** (see Glossary) [6] and extinctions [7], there has never been greater urgency to document the estimated 20% of the Earth's flora that remains to be scientifically described [8]. Comprehensive syntheses of information about individual plant groups underlie all kinds of research, the conservation of plant diversity [9], sustainable and fair use [10], and science outreach activities to improve awareness of plants [11]. **Monographs** are a key resource for **taxonomists**, and are widely used in fields such as ecology, genetics, evolutionary biology, palaeontology, and applied contexts, including horticulture, conservation, natural resource management, and plant breeding. For over 300 years, monographs have also been the standard way in plant sciences to disseminate authoritative scientific information about plant species, genera, and families (Box 1).

Monographs stimulate species discovery and slow the decline of undescribed biodiversity by providing the baseline information to address the environmental emergencies of the Anthropocene [12,13]. The comprehensive classification and comparative data presented in a monograph together allow unidentified specimens to be more readily recognised as a known taxon or confirmed as a species new to science. This is exemplified by the recognition of 38 new species since the publication in 1995 of a comprehensive monograph of the palms of Madagascar [14]. Indeed, this monograph led to a 23% increase in known endemic species, almost all of them at risk of extinction [14,15]. Monographs of ecologically important lineages are also vital for addressing environmental challenges. A recent monograph of *Eucalyptus* (Myrtaceae) [16], together with related authoritative information resources (e.g., IUCN Red List extinction assessments[ii] and detailed occurrence records in the *Atlas of Living Australia*[iii]), could support the design of ecosystem

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Box 1. What Is a Botanical Monograph?

A botanical monograph is a thorough systematic treatment of a plant group drawn from observations of plants in their native habitat, specimens in reference collections, and data generated in the laboratory. These treatments articulate the taxonomic decisions made by experts using multifaceted evidence summarised for species in the group. The research process is similar regardless of the size or scale of the group treated, but the scope varies [13]: in the traditional sense, a monograph covers all taxa within a family or genus (e.g., *The Genus* Inga [69]), whereas a regional monograph covers one region (e.g., *Palms of Madagascar* [14]). A broader view includes formats such as the annotated checklist, Flora or field guide, and treatments of ecological or functional assemblages (e.g., succulent plants [59,60] or mangroves [70]). With ever-improving resolution in the Tree of Life, it is now conceivable that a monograph covers a clade within a family or even order. Monographs include species names, descriptions, data on distribution and habitat, taxonomic **nomenclature**, specimens consulted, maps, photographs, and illustrations. Various other data types may be included [13], such as a Tree of Life (phylogeny) and data pertaining to the genome, cytology, micromorphology, conservation, extinction risk, georeferenced localities, and adaptive traits of the species. Monographs are most frequently consulted for species descriptions and distribution data; photographs, phylogenetic trees, and data describing human uses of plants will be particularly important in addressing users' needs in future. Most monographs are published as books, or as a series of volumes, or journal articles (e.g., *A Taxonomic Monograph of Ipomoea Integrated across Phylogenetic Scales* [42]), and increasingly, to enhance accessibility, they also become online searchable resources (e.g., Solanaceae Source[xx]).

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recovery measures in Australia following the 2019/2020 bushfires that destroyed in excess of 5.8 million hectares [17] of vegetation. The coronavirus disease 2019 (COVID-19) pandemic of 2020 has further drawn attention to the importance of comprehensive taxon information to support decision-making around how the Earth's natural resources should be managed to minimise future risk to both humans and biodiversity[i], while promoting the economic benefits of biodiversity within the context of the **Convention on Biological Diversity** [2,3,10].

Conversely, the lack of monographs has significant negative effects on downstream research, conservation, and sustainable use of both cultivated and wild plant diversity. The absence of comprehensive taxonomic accounts and **phylogenetic** frameworks has limited the understanding of plant diversification, to the extent that the closest related species of many major crops remain unknown or contentious (e.g., sugarcane, *Saccharum officinarum*; Poaceae [18]). Confusion regarding the taxonomic status of crops and their wild relatives can misinform and ultimately mislead crop breeding efforts, conceal historic centres of domestication where undiscovered genetic diversity may yet be found, confound germplasm conservation efforts [19–21], and limit the use of botanical collections [22]. For wild plant groups, the lack of a monograph amplifies the risk that a species becomes extinct before it can be conserved or scientifically described and studied.

Innovations in Centuries of Tradition

Over the centuries, monographs have provided the backbone to much of the world's research on plants. The data compiled in monographs (Box 1) reflect scientific advances in documenting plant diversity [9,23–25] and illustrate trends in the knowledge deemed useful since the first plant monograph was published during the 17th century [26]. To meet the needs of today's users (Box 1), monographs must continue to integrate new data sources and be widely accessible, while also being produced and updated more rapidly: monographs are still needed for most of the world's plant genera.

The advent and expansion of internet and digital technologies (including photography) during the 20th century revolutionised how monographs were undertaken and illustrated. Technologies available during the 21st century must now be harnessed to accelerate progress where it is most urgently needed [27]. Community approaches are strongly recommended because they have demonstrably aided progress [23,28], particularly for some of the largest and most economically important plant families, including the daisies (Asteraceae/Compositae) [29], legumes (Fabaceae/Leguminosae) [30] and grasses (Poaceae) [31]. Collaborative efforts have also benefited national and regional Flora projects, giving rise to comprehensive online treatments of highly diverse regions, such as the *Flora of Brazil*[iv], *Flora of China*[v], and *Flora Mesoamericana*[vi]. An integrated, collaborative, and global approach to taxonomy and monography gained momentum during the early 2000s, driven by the aspiration of the international botanical community to compile a complete world flora online and a unified source of plant morphological (trait) information [32,33]. Following advances such as the DELTA platform for online structured species descriptions[vii], the European Union invested in an open web platform for taxonomy, Scratchpads [34], as part of the European Distributed Institute of Taxonomy (EDIT) project, while the National Science Foundation of the USA supported Planetary Biodiversity Inventories [35]. Online monographs for plant families, such as the Euphorbiaceae[viii], Caricaceae[ix], and Sapotaceae[x], streamline constant updates, but depend on institutional taxonomic and technical support. e-Taxonomy efforts have helped to deliver cost-efficient, authoritative resources in highly biodiverse but often low-income regions [36,37], and to mobilise the global collections held in wealthy countries [38], and will be critical to scaling up monography in the Anthropocene.

Advances to resolve the **Tree of Life** [39] and the revised classification of flowering plants [40] have influenced further methodological changes (see later). The 'foundation monograph' [41] demonstrated the advantage of simultaneously sequencing specimens consulted during the preparation of a monograph to refine species concepts and identify clades or biological units in need of more detailed study [28,41,42]. Efficient high-throughput sequencing technology now offers the prospect of sequencing the millions of specimens deposited in the world's **herbaria** ('herbariomics') almost regardless of their age and preservation status [43–45]. With these advances, a phylogeny providing the evolutionary framework for a revised classification is no longer the problematic bottleneck in the monographic process that it used to be. A complete phylogeny prepared in advance expedites the subsequent taxonomic revision [46] and data synthesis needed to produce an integrated monograph that builds on multiple data sources, as well as providing the evolutionary framework for research beyond the monograph. Complete phylogenies are conceivably within reach for thoroughly sequenced plant genera, such as the aloes (c. 600 species, Asphodelaceae) [47], entire tribes, such as the Bignonieae (400 species, Bignoniaceae) [48], and large families, such as the palms (Arecaceae, 181 genera, 2600 species) [49] for which previous monographs have necessarily focussed on individual genera due to poorly resolved family-level phylogenies. With the availability of reference genomes for model and non-model plant genera likely to improve within the next few years [50], the upward trajectory for incorporating '-omics' data into monography is expected to continue.

Where Can Monographs Have the Greatest Impact?

Monographs unlock the potential of the plant kingdom as a resource to address urgent planetary challenges, from hunger to energy [51]. Progress towards monographing and sequencing the Earth's c. 346 000[xi]–351,180 [52] vascular plant species has often been contingent on the size

Box 2. Progress toward Monographing the Earth's Plant Diversity

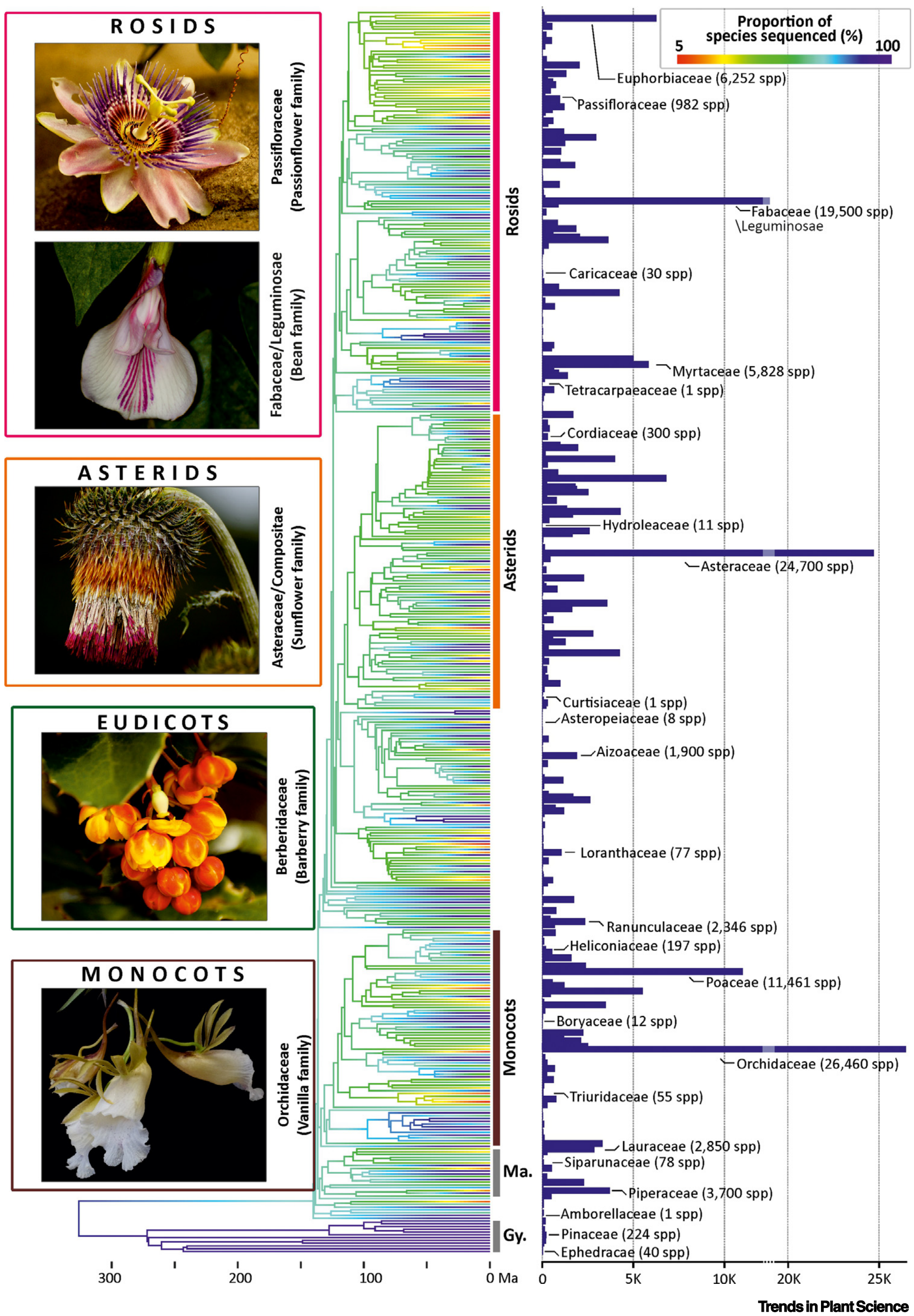
Phylogenetic trees estimated from DNA sequences are the framework for integrated monography. Larger families of flowering plants tend to be represented by a lower proportion of sequenced species (see Figure 1 in the main text and Figure S1 in the supplemental information online) and are less likely to have been monographed (see Figure 2 in the main text). More sequences are, proportionally, available for genera already treated in a monograph (see Figure 2 in the main text), reflecting the activities of dedicated research programmes building molecular phylogenies that inform the classifications presented in monographs. These patterns were identified by surveying published monographs and commonly sequenced loci (ITS, *Xdh*, *atp*B, *mat*K, *nad*5, *psb*A, *rbc*L, *trn*L-F, *rpl*32, and NADH) sequences in GenBank[xxi] among the angiosperm genera in *Plants of the World Online*[xiv]. An online literature search for any taxonomic revision or synopsis that treats 80% or more of currently accepted species was conducted for 200 randomly sampled genera from four size class quartiles of angiosperm genera. The patterns point to the resourcing and collaborative efforts necessary to address the need for more monographs.

Glossary

Convention on Biological Diversity: a multinational agreement[xxii] with three main goals: the conservation of biodiversity; the sustainable uses of its components; and the fair and equitable sharing of benefits arising from genetic resources.
Herbarium: a reference collection of mounted dried plant specimens used for scientific study.
Monograph: a compilation of information of a family or genus, including a taxonomic treatment, descriptions of species, and a variety of data and illustrations to synthesise all known information about the group. The practice of preparing a monograph is called monography.
Nomenclature: in the natural sciences, the system of names applied to living things, including plants, governed by the International Code of Nomenclature for algae, fungi, and plants.
Phylogeny: diagram representing the Tree of Life and evolutionary relationships between the represented taxa.
Range shifts: changes in the geographical range occupied by a species, which may contract or expand to match the availability of its ecological niche.
Taxonomy: the science of defining taxa and classifying organisms based on shared characteristics.
Tree of Life: a diagram showing how all life on Earth is related by common descent.

Key Figure

Progress towards Sequencing the World's Flora Shown on the Tree of Life for Seed Plants [68]



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of the plant group (Box 2). Even species recorded in important global data sources, such as the Global Biodiversity Information Facility (GBIF[xii]) describing plant occurrences and the TRY Plant Trait Database[xiii], may not have been extensively studied [25]. Although numerous, these records are not necessarily taxonomically or geographically representative due to inherent biases in plant distribution data and research [25,53] and the problems associated with the misidentification of those records [54]. Such issues can affect even the relatively well characterised plant superfamilies, because they support much of the world's food, fodder, and fuel provision (e.g., legumes, Fabaceae/ Leguminosae, 19 500 species [30]; and grasses, Poaceae, 11 290 species [55]) and are integral to ecosystem and land management strategies for food provision and carbon storage or to reduce CO_2 emissions [56]. Nonetheless, these superfamilies have yet to be comprehensively monographed, despite the efforts of dedicated research teams working at the genus and species levels.

Criteria for Prioritising Monographic Efforts

To maximise the use of resources in a time of rapid global change, it is now essential that botanical organisations and their researchers prioritise efforts. Strategies should consider plant groups with ecological, economic, or cultural importance, and how new efforts will contribute to fill current knowledge gaps in plant diversity, systematics, evolution, and conservation (Box 2). An important step to achieve these goals is integrating new data more efficiently, starting with a phylogenetic framework. We propose the following criteria to guide the selection of plant groups in most urgent need of monographic study:

(i) Major knowledge gaps: large groups that have not been monographed in the past c. 150 years (e.g., the genus *Croton* in Euphorbiaceae, with >1000 species[xiv]) and include many species that cannot be evaluated for extinction risk due to taxonomic complexity limiting the allocation of species names; (ii) threatened: groups considered to be at high risk of extinction, or including both threatened and non-threatened species that are difficult to identify, are rare, or in urgent need of conservation assessment (e.g., the orchid family Orchidaceae, especially south-east Asian groups, such as *Vanda* [57]); (iii) valuable: groups that benefit ecosystems or humanity, identified by indicators such as a high proportion of crop wild relatives or rainforest tree species, as well as species of ecological, economic or cultural value, nitrogen fixation, carbon storage, or climate change resilience. For instance, a comprehensive monograph is needed for the legume tribe Phaseoleae, which includes the many crop wild relatives of cultivated beans (*Phaseolus*); (iv) morphologically or functionally unusual: groups that represent rare and extreme combinations of functional traits, at the fringes of the global spectrum of plant form and function [58], could illuminate potentially valuable adaptations to environmental change. Ecologically or functionally defined monographs, such as the multi-volume *Illustrated Handbook of Succulent Plants* [59,60], might also be considered for groups such as (salt-tolerant) halophytes, or plants used for phytoremediation to improve contaminated soil and water, or to fix nitrogen for soil enhancement; and (v) strategic: genera, such as *Myrcia* (c. 800 species of south American Myrtaceae [9]), for which a collaborative monograph could be readily accomplished using available phylogenetic information [61], herbarium reference collections, and taxonomic expertise.

Applied against the backdrop of progress to sequence and describe the world flora (Box 2, Figure 1, Key Figure, and Figure 2; see also Figure S1 in the supplemental information

Figure 1. Branch colours indicate the proportion of species sequenced in each family, based on a survey of traditional barcode loci available in GenBank. Bar plots to the right show per-family species numbers, with selected important families labelled. Sequencing efforts vary widely across the Tree of Life, with lower levels of sequence availability generally observed among the most species-rich families (e.g., orchids, Orchidaceae) despite notable exceptions, such as the grass family Poaceae. Also see Figure S1 in the supplemental information online. Abbreviations: Gy., gymnosperms; Ma., Magnoliids; spp, species.

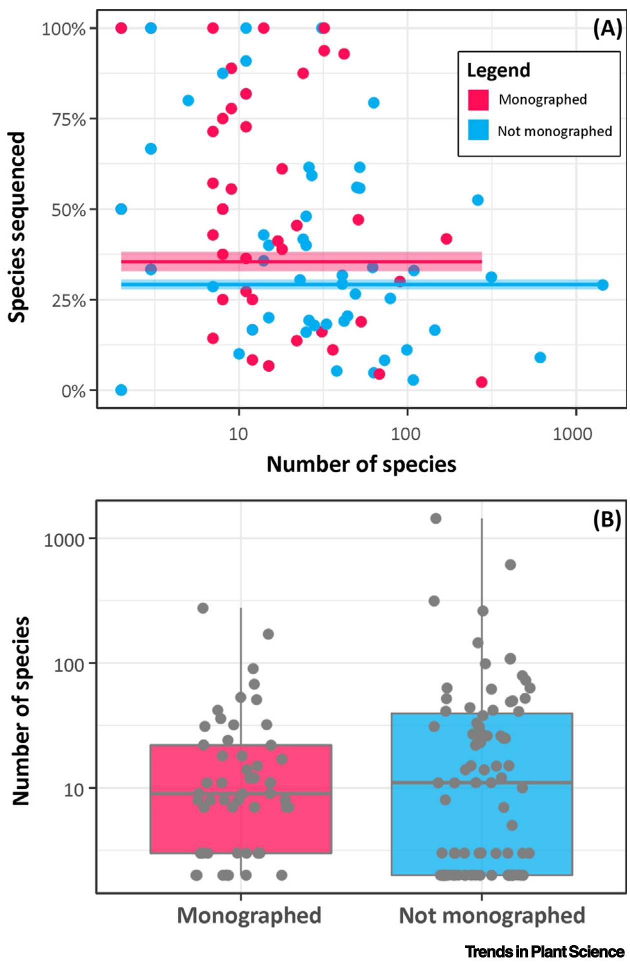

Figure 2. Monographs of the World's Plant Genera in Relation to Their Size and to the Proportion of Species per Genus That Have Been Sequenced, Based on a Stratified Random Sample (See Also Figure S1 in the Supplemental Information Online). The box plot (A) compares species number per genus, in sampled genera with and without monographs. The scatter plot (B) shows the number of species for which sequences are available in the sampled genera with and without monographs. This figure shows that the probability of being sequenced is not equal for all species, with species in larger genera being less likely to be sequenced than expected by chance. Similarly, species in genera lacking a monograph were less likely to be sequenced than expected and, of those sampled, monographed genera contained fewer species in total than did genera lacking monographs.

online), these criteria overwhelmingly intersect on plant groups with centres of species diversity in the tropics as priorities for future work. Tropical latitudes are disproportionately biodiverse and impacted by environmental degradation [62,63], yet are inadequately represented in the botanical collections [24] that support species discovery. Such imbalances have long been apparent in the number of herbarium specimens available [8,25,64] and monographic progress, and are a matter of urgent concern, given that about half of the new species named each year are discovered among specimens in herbaria [65]. The function of herbaria as a reference collection for plant identification cannot be overstated. Herbaria can also be mined for specimen metadata to rapidly and efficiently fill gaps in global baseline repositories [25,64,65] in addition to tissue samples for sequencing and analysis [see (ii) earlier] during the monographic process.

Concluding Remarks and Future Perspectives

The urgent challenges and unparalleled opportunities in the Anthropocene mean that monographs are more relevant than ever. Monographers have an opportunity to contribute the comprehensive, taxon-level data required for effective responses to planetary crises [2–4]. It is important to outline what best practices in monography look like. We emphasise here the necessity for multilateral collaboration to facilitate global access to digital and physical

Outstanding Questions

How should the botanical community identify shared priorities to expedite the completion of monographs of plant superfamilies with large global distributions? Economically important plant families, such as grasses, legumes, and orchids, have been studied by collaborative teams of scientists but comprehensive monographs treating all species in these families are not yet available, due to the scale of the challenge. These superfamilies comprise tens of thousands of species and are found almost everywhere on Earth. Advances in building the plant Tree of Life and accessibility of digital tools now make it possible for community efforts to be channelled to shared goals.

How best can monographers share the diverse data generated while compiling a monograph? The trend to produce Open Science means data are readily available in rapid and efficient ways but accessing them can be challenging. Global efforts to develop the extended specimen concept [66] can be embraced to facilitate sharing of the many digital and physical resources [67] agreed to standardised formats and amenable for synthetic analyses associated with the specimens consulted in the preparation of a monograph.

How can partnerships within and between the biodiverse but often low-income countries and wealthy, mostly temperate, countries be best structured to fill gaps in monographs in the most collaborative, mutually beneficial way? Extraordinarily diverse tropical plant groups for which monographs are most urgently needed are concentrated in biodiverse but low-income countries. Sharing specimen images assists in levelling collaboration between low-income and wealthy regions, but the needs of taxonomic communities must be jointly articulated to best progress productive and equal collaboration on the most urgent monographic tasks. Partnerships are needed to make the data of reference collections accessible via a single search.

specimens, which represent the primary sources of information for monographs, according to the standards for Access and Benefit Sharing articulated by the Convention on Biological Diversity [10,22]. Taxonomic efforts are most urgently needed to support actions that halt biodiversity loss. Monographers are now well equipped to address historic imbalances to resolve the problem of unnamed species diversity and, most importantly, provide and support the expertise and tools needed to deliver taxonomy that is relevant to the widest audiences (the 'taxonomic impediment' [37]). Extraordinarily diverse tropical plant groups for which monographs are most urgently needed are concentrated in countries where the necessary resources, sometimes even taxonomic expertise, may be lacking. Networks of organisations could facilitate discussions among these countries to jointly agree priority plant groups, establish shared monographic projects, exchange materials, and undertake targeted field expeditions to discover and document the unknown. Partnerships are also needed among the (mostly temperate) institutes holding global reference collections, to make their data repositories accessible via a single search.

The legacy of over 300 years of monographic tradition reaches far beyond library shelves and specimens in herbaria. Today, monographs are a vital aid to develop rapid and accessible species identification and dissemination tools that will support crucial interventions [66] and governance in the context of intense and unprecedented anthropogenic forces [67]. Addressing these environmental challenges calls for a careful prioritisation of plant groups and efficient workflows so that the most limiting knowledge gaps are filled urgently with new monographs (see Outstanding Questions).

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Supplemental information

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Resources

[i] https://ipbes.net/covid19stimulus
[ii] www.iucnredlist.org
[iii] www.ala.org.au
[iv] http://floradobrasil.jbrj.gov.br
[v] www.efloras.org/flora_page.aspx?flora_id=2
[vi] www.tropicos.org/project/fm
[vii] www.delta-intkey.com/angio/index.htm
[viii] http://app.tolkin.org/projects/72/taxa
[ix] https://herbaria.plants.ox.ac.uk/bol/caricaceae
[x] https://padme.rbge.org.uk/sapotaceae/index.php
[xi] https://wcvp.science.kew.org
[xii] www.gbif.org
[xiii] www.try-db.org
[xiv] www.plantsoftheworldonline.org
[xv] www.inaturalist.org/pages/seek_app
[xvi] www.plantsnap.com
[xvii] www.mapress.com/j/pt/index
[xviii] https://plants.jstor.org
[xix] http://biodiversitylibrary.org

xx http://solanaceaesource.org

xxi www.ncbi.nlm.nih.gov/genbank

xxii www.cbd.int/

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