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Perspective

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High-performance living plant collections require a globally integrated data ecosystem to meet twenty-first-century challenges

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Documented living plant collections distinguish botanic gardens from other green spaces and horticultural landscapes. With more than 3,500 collections worldwide, these institutions steward at least 105,634 species—around 30% of all land plant diversity—while fulfilling amenity, educational, scientific and conservation roles. However, twenty-first-century challenges demand a re-evaluation of how these collections are documented and managed. We argue that meeting these emerging needs requires higher standards of coordinated information management and innovation in data infrastructures across the global network. This Perspective critically examines data management practices of living collections supporting scientific research and conservation, from institutional to global levels. We identify the renewed demands on living collections, highlight exemplar global data infrastructures, define data challenges inherent to living collections and explore how current systems fall short in enabling a connected global system. Finally, we outline a vision for high-performance collections, fully integrated into a robust global data ecosystem.

Globally, there are more than 3,500 documented living plant collections, collectively stewarding a staggering minimum of 105,634 plant species, encompassing 30% of all land plant species diversity[1]. The living collections have long been an asset for vital and traditional scientific disciplines such as taxonomy and systematics[2]. But a revitalized scientific role for diverse living collections is also being driven by new and evolving scientific disciplines[3–5] that depend on access to well-provenanced and taxonomically verified material. For example, genomics requires living material for the isolation of high-molecular-weight DNA for long-read sequencing, for optical mapping techniques to enable chromosome-level assembly and to obtain RNA for comprehensive genome annotation[6]. Dramatic reductions in genome sequencing costs have increased the ambition of sequencing initiatives, with programmes such as the 1000 Plant Transcriptomes project[7] and the Global Genome Initiative for Gardens that require ready access to plant collections[8]. The revolutionary synthesis of metabolomics and transcriptomics, facilitating the rapid characterization of biosynthetic pathways and bio-industrial production of high-value chemicals from plants, thrives with access to taxonomically diverse collections. Living collections have the potential to support the biomimetic study of plant structures, processes and systems that can support innovative technologies and solutions in engineering and design[9–12]. Finally, plant biology has re-entered a progressively comparative era, in which biological models and knowledge, derived from relatively few laboratory-based organisms, are increasingly tested against an expanding array of diverse species[13].

In addition to renewed scientific demands for diverse living material, the living collections held by botanic gardens are increasingly viewed as a vital ex situ repository for biological and cultural plant diversity[14], including species that are threatened with extinction in native habitats[15–17], and especially exceptional plant species that cannot be conserved using conventional seed bank methods[18]. More than 40% of the world's plant diversity has been estimated to be at elevated risk of extinction. The extinction threat is largely deemed anthropogenic, including habitat degradation, introduction of invasive species, resource overexploitation and climate change[19]. The central role of living collections in the conservation and management of plant diversity rests on the assertion that no plant species should become extinct,

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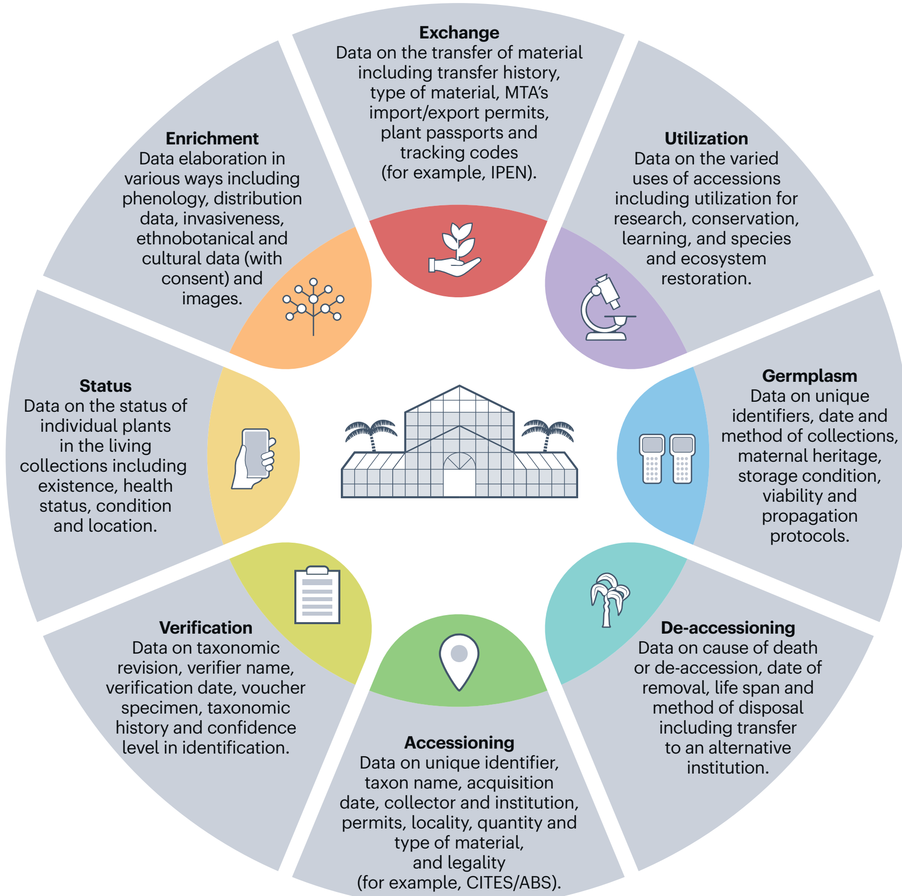

Fig. 1 | Key data domains for a living plant collection. This diagram illustrates exemplar categories of data required to manage a living plant collection. At the centre is a symbolic representation of a botanic garden, surrounded by eight essential domains of data: accessioning, verification, status, enrichment, exchange, utilization, germplasm and de-accessioning. Each domain encompasses specific types of information vital for tracking plant material throughout its life cycle—from acquisition to eventual removal. These interconnected data categories underpin the stewardship of living collections and collectively generate the data needed to support a metacollection model for global living plant collections management. ABS, Access and Benefit Sharing; CITES, Convention on International Trade in Endangered Species of Wild Fauna and Flora; IPEN, International Plant Exchange Network; MTA, Material Transfer Agreement.

given the array of ex situ and in situ conservation techniques such as seed banking, cultivation in living collections, tissue culture, species recovery and ecological restoration[16]. In the context of the Global Strategy for Plant Conservation, living collections were seen as being key to achieving Target 8 (now Target 4 of the Kunming-Montreal Global Biodiversity Framework), which called for at least 75% of threatened plant species in ex situ collections (preferably in the country of origin) and at least 20% available for recovery and restoration programmes. As anthropogenic climate change promises to outpace the ability of many plant species to migrate, one proposed solution is assisted migration, in which species would be intentionally transferred into locations they might have reached were climate change occurring at a slower pace[3]. Although controversial, a role has been proposed for a globally distributed network of living collections to chaperone the assisted migration process, as well as monitoring negative consequences such as invasiveness and unwanted hybridization in migrated species[20]. In the context of increased global movement and trade, living collections can also serve as a vital early warning system—for example, the International Plant Sentinel Network[21] detects and shares information about new and emerging pest and pathogen risks.

The delivery of strategic objectives in science and conservation is in part dependent on the concept of the "metacollection"[22]: a coordinated network of living collections that collaboratively steward and provide access to the world's plant diversity. Collaboration is essential, as individual institutions have varied but ultimately limited capacities to cultivate plant diversity, constrained primarily by resources and ecological niche: a point illustrated by recent analyses that indicate that many living collections have reached peak capacity and diversity[23]. In this context, a global metacollection has greater potential to hold the necessary species and intra-specific genetic diversity. But a metacollection also requires effective coordination across a globally diffuse network of ex situ diversity, with seamless flow and exchange of information, which is, in turn, contingent on robust and efficient data management.

Data are fundamental to high-performance management of living collections

Managing hyper-diverse assemblages of plants under dense cultivation and within constrained environments demands robust data management—an operation usually visible only as a façade of labelled plants. Effective information management systems and processes are essential to the performance of living collections. Every batch of plants, termed an accession, is tracked and monitored from the moment they are sourced to the time they leave the collection (Fig. 1). Throughout this life cycle, actions around an accession are recorded, including processes such as sourcing, accessioning, mapping, verification, propagation, auditing, herbarium vouchering, seed banking, material transfer, utilization and de-accessioning. Accessions often accumulate additional valuable data through primary observations on phenomena such as phenology, hardiness, edaphic conditions and pest or disease susceptibility, as well as secondary data acquisition such as consented description of ethnobotanical uses, extinction risk and biogeographic distribution. The sheer volume of data generated through these processes necessitates specialized databases and skilled personnel to ensure the long-term integrity and utility of this information.

The value and utility of living collections are then defined by the quality and quantity of their associated data, as well as their integrity with the specimens, with the potential applications and outcomes for an accession intricately tied to this information in numerous ways (Fig. 1). For example, the presence of complete and accurate legal documentation, such as export and import permits, is crucial for determining an accession's availability to external stakeholders. Even when legally acquired, associated data may reveal restrictions that limit a specimen's use for scientific research or commercial development. Provenance data, indicating whether an accession originated from the wild or has a history of cultivation, influence its conservation value and potential for species reintroduction[24–26]. For wild-sourced material, the propagation method—whether vegetative or reproductive, controlled or uncontrolled—affects genetic stability and conservation utility[27–29]. Inaccurate location data within a collection can delay or hinder accessibility and utilization, whereas taxonomic errors, such as misidentified species or the use of outdated synonyms, can discourage or even prevent use entirely. Ultimately, poor-quality data can lead to an institution underestimating the significance, value or utility of an accession, potentially resulting in unjustified de-accessioning and permanent loss from the collection.

In recent decades, advances have been made in the management of data for living collections. Since the early 1990s, we have witnessed the transition from analogue to digital systems, with the emergence of sophisticated databases capable of managing vast quantities of accession-level information[30]. Widely adopted commercial platforms such as BG-BASE[31] and IrisBG[32] as well as institution and community-specific platforms such as Living Collections Management System[33] and Botalista[34] have enabled institutions to streamline data entry, improve data accuracy and integrate data across multiple processes. The German Gardens4Science programme has developed a platform based on wrapping technologies and data standards to allow the curation of distributed collection data as well as standardized data aggregation and data access pipelines based on established community protocols[35]. Meanwhile, Botanic Gardens Conservation International (BGCI) have created global repositories for living collections and their collections data such as PlantSearch, GardenSearch and ThreatSearch. International databases such Plants of the World Online[36], World Flora Online[37], International Union for Conservation of Nature and other red lists[38], and the Global Biodiversity Information Facility[39] are also facilitating a culture of data sharing and collaboration, with individual living collections beginning to connect to a global network of biodiversity information. Collectively, these advances have strengthened the ability of living collections to support global biodiversity goals. But nonetheless, critical deficiencies persist.

Addressing the challenges in the current living collections data architecture

Before addressing specific challenges, it is worth reflecting on examples from other collection domains that demonstrate that large-scale, coordinated infrastructure development is achievable and transformative. Initiatives such as iDigBio in the USA have successfully mobilized hundreds of millions of preserved specimen records into a unified digital resource[40], whereas DiSSCo in Europe are building distributed infrastructures to integrate diverse natural science collections within a common data framework[41]. The Global Biodiversity Information Facility has likewise shown the power of coordinated international infrastructure by aggregating more than three billion biodiversity records into a single open platform[39], albeit with still limited data input from living collections. These efforts show that, with sufficient coordination, investment and standards, fragmented data systems can be networked into powerful global resources that support science, conservation and policy. Building on these precedents, the living collections community has a clear opportunity to adopt similar strategies and adapt them to the distinct requirements of accession-level living collections data. But despite the importance of data for defining the identity and function of these living collections, notable challenges remain in the current information infrastructure, as discussed below.

Fragmented database ecosystem

Our data infrastructure and processes exhibit important disparities at a variety of different geographic scales. A large proportion of botanical ex situ collections, possibly up to two thirds[1], remain non-digitized or lack advanced digital database solutions. Even among collections with digital databases, fragmentation is a persistent issue, with institutions relying on in-house systems of varying complexity or a limited number of competitive commercial platforms. These commercial solutions, while sometimes innovative, are often financially prohibitive—particularly for institutions in the Global South—and offer no guarantee of long-term stability owing to competition, market fluctuation and shifts in provider dominance. An additional challenge is that most platforms are not multi-lingual, in contrast to the linguistically diverse communities of users, leading to regional and national use of different systems. Collectively, these factors hamper the integration and optimization of botanical data infrastructure on a global scale.

Limited adoption of data and process standards

The fragmented nature of living collections management is exacerbated by the lack of universally accepted data and process standards. This deficit is more noticeable when compared with other collection types, such as the SPECTRUM collections standard for museums, Darwin Core standards[42], or the Minimum Information about a Digital Specimen measures[43] currently being specified within the TDWG Biodiversity Information Standards[44]. Although many living collections strive to maintain high standards in management practices, substantial variability persists, even among well-established collections. Initiatives such as the International Plant Exchange Network and BGCI's International Transfer Format have made progress in standardizing certain processes, but a unified framework for minimum data standards, consistent data entry and standardized data formats remains elusive. Consistent data standards and processes become particularly important when attempting to maintain the genetic integrity of threatened plant species. More broadly, the limited use or application of digital data standards hinders data sharing, specimen exchange and the wider integration of living collections into global biodiversity initiatives, limiting their collective impact and potential.

Lack of a transparent and open data culture

Botanic gardens often struggle with transparency regarding the contents and provenance of their living collections, with its origins in a historical culture of competitive collecting practices. More contemporary concerns include unwanted attention or theft of specific accessions and apprehension about sharing data for accessions that have not yet been subject to comprehensive curation and data checks. Paradoxically, sustaining the flow of plant diversity relies on building trust—particularly between collection holders and biodiversity-rich countries or providers[45]. Open data are essential to fostering this trust, linked to material that is accessible, legally compliant and securely managed (that is, FAIR[46] (findable, accessible, interoperable and reusable) and CARE[47] (collective benefit, authority to control, responsibility and ethics) principles). Without such transparency, achieving the trust necessary for meaningful global collaboration becomes less likely.

Poor integration with global data source and cognate collections

Global data management for living collections largely functions as a closed information system, with access to global datasets often

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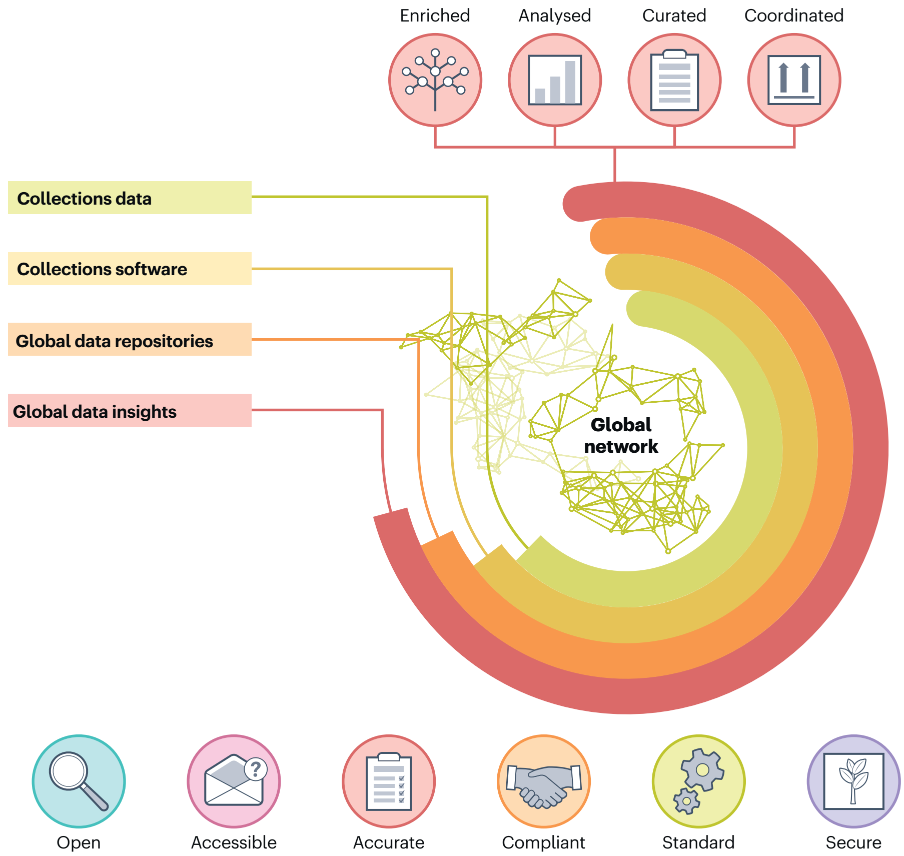

Fig. 2 | Data integration pathway for high-performance living collections within a global data ecosystem. This diagram illustrates the transformative flow of collections data as it progresses through layers of digital infrastructure to generate enriched global insights. Starting with institution-level collections data (green) managed via collections software (yellow), information feeds into global data repositories (orange) and ultimately produces global data insights (red). As data move through this pathway, they become progressively enriched, analysed, curated and coordinated—enhancing their strategic value for research and conservation. At the foundation of this system are six core data governance principles—open, accessible, accurate, compliant, standard and secure—which ensure data integrity, interoperability and ethical use throughout the global network.

restricted, and with limited integration with institutional living collections databases. This lack of connectivity hinders the seamless use of global datasets within individual living collection data management systems, and vice versa. Consequently, living collections are commonly out of date with respect to International Union for Conservation of Nature Red List datasets, preventing the timely identification of ex situ cultivated species that are newly threatened or facing increased extinction risks. Likewise, limited integration with resources such as World Flora Online restricts the adoption of the latest taxonomic consensus and biogeographic data in a uniform way across collections.

Although repositories such as BGCI's PlantSearch collate data on the contents of living collections, these data are not integrated with individual collections with sufficient frequency, and consequently botanic-garden-derived data in global repositories are patchy and out of date. Additionally, there is limited networking with increasingly comprehensive data infrastructure built around cognate collection types (for example, the Global Genome Biodiversity Network[48] (for tissue and DNA banks) and GENESYS[49] (for food crop seed banks)).

Limited tools for strategic prioritization and visualization

Accumulated data from living collections have the potential to provide profound insights into collection management but remain massively underutilized. Longitudinal analyses that leverage historical collections data present an opportunity to track the performance and trajectory of metacollections over time[23]. Contextual data tools and analyses can enable the evaluation of living collections within regional or global contexts[50], helping assess the value of species in cultivation[50–52]. Rarity assessments can inform gap analyses, revealing the absence of specific threatened and endemic species across collections, as well as biogeographic and taxonomic gaps[1]. And crucially, effective niche modelling, when integrated with gap analyses[1,18], can help prioritize the strategic acquisition and distribution of at-risk species in the face of climate change[25]. However, the general absence of effective and freely accessible tools for data-driven prioritization of space and resources remains a clear limitation in addressing the challenges posed by the biodiversity extinction crisis.

Our vision for a globally integrated data ecosystem for living collections

Our vision begins with a reaffirmation of the extraordinary nature of our globally distributed living collections and the pivotal role of their data. These collections can be likened to a vast, slow-moving river of germplasm—dynamic and constantly shifting, yet carefully channelled and harnessed for various purposes. Managing this flow of biodiversity is inherently challenging, but it generates an abundance of data and information that are invaluable not only to the botanic garden network but also to a wide range of stakeholders. These data, uniquely produced by managed living collections, distinguish us from other biodiverse landscapes and are key to our identity. Supported by these data, we define our singular roles, our immense potential to tackle societal challenges and our pathway to the integrated management of plant diversity.

At the heart of realizing our vision lies cultural change, with adherence to six fundamental principles governing living collections data

(Fig. 2), aligned to the FAIR and CARE principles[46,47]. For our global network to sustain the necessary technological advancements for a unified data system, these principles must garner widespread acceptance. These six principles require collections data to be: open—our data are openly searchable by stakeholders and peers; accessible—the material linked to our data is accessible for use by the community and stakeholders, including research, education and conservation practitioners; accurate—our data are up-to-date with respect to the material they describe, and accurate with respect to taxonomic consensus and conservation status; compliant—our data are held to the highest legal standards and consistent with national and international laws governing collections, data and their use; secure—our data are securely preserved in perpetuity, with mitigation against current and future risks; and standard—our data are structured and organized to allow for full integration of data and processes between collections across the global network. The cultural adoption of these principles is key to providing the foundation and support for the vision of a data infrastructure that will require considerable redesign and innovation.

Our vision is to establish a globally integrated system that enables seamless management of the world's ex situ plant diversity (Fig. 2). At its core, this system would feature a standardized yet adaptable database infrastructure—affordable, scalable to collections of all sizes and flexible enough to support locally adapted workflows as well as both public and commercial software. To ensure maximum interoperability, it is essential that both standards and infrastructure components build on existing developments and avoid parallel structures wherever possible. By prioritizing accessibility, particularly for currently undigitized collections in the Global South, we aim to ensure equitable participation in the global conservation effort. Developed through collaborative design, funding and maintenance, this architecture would foster widespread adoption of minimum data standards and consistent formats, enabling effortless digital data exchange across collections and integrated global portals. Automated and routine data transfers would allow individual collections to share sourcing information, including precise provenance data, while global repositories would provide up-to-date conservation assessments and taxonomic consensus. Regular synchronization between local and global databases would empower the community to track the movement of plant diversity as species and accessions are added, shared or lost.

Advanced analytical tools—such as niche modelling and gap analysis—would be freely accessible, supporting decision-making, particularly in acquiring intraspecific genetic diversity and allowing planned acquisition in the face of climate change. Global data platforms would facilitate material exchange between collections and external users, enhancing the value of living collections for research and conservation. These platforms would also track and visualize the movement of genetic material, improving transparency and compliance. Sharing protocols would strengthen horticultural efficiencies and support in situ species reintroduction efforts. Strategic de-accessioning would be guided by enriched data and a broader conservation context. Training programmes would ensure that curators, horticulturalists and data specialists have the skills to access and apply the data tools to support the management of individual and networked collections. Together, these efforts would create a resilient, data-driven system, generating outputs that are enriched, curated, analysed and coordinated, advancing the role of botanic gardens in safeguarding and stewarding plant diversity worldwide.

Recent advances in data management and collaboration fuel optimism that a globally integrated data ecosystem for living plant collections is within reach. First, as mentioned, botanic gardens have begun linking their databases and sharing information as never before. For example, BGCI's platforms provide a nascent data network—PlantSearch alone hosts more than 1.4 million records from more than 1,100 collections, and ThreatSearch has compiled more than 300,000 plant conservation assessments. These shared resources, together with a universal taxonomic backbone (for example, World Flora Online), provide a solid foundation for further interoperability. The concept of a distributed metacollection—as an integrated global collection managed across many gardens—is gaining traction. Some botanic gardens are pioneering the application of metacollection practices and processes developed in the zoo and aquarium communities and applying them to botanical metacollections[27]. At the same time, new collaborative networks are forming to use data in coordinated action[53]. Notable national examples of concerted muti-institutional action around ex situ conservation include the Wildpflanzenschutz Deutschland project and the regional Hawaiian Rare Plant Program[54]. At a global scale, the recently established Global Conservation Consortia link experts and gardens around the world to craft collective strategies for at-risk plant groups, demonstrating the power of data-driven collaboration[55]. Shared taxon-specific ex situ programmes for conifers, cycads, oaks, magnolias and ericas show that when institutions pool data, expertise and resources, they can achieve outcomes that would have been impossible in isolation[23,55,56].

Conclusion

Here we have focused on the living collections data ecosystem, because many aspects to managing these collections are unique within the broader collections sector. But we can look to the more advanced and better-networked accession-level data systems of ex situ agricultural gene banks[57] (for example GENESYS[49]), not only for inspiration but with a view to lessons learned, and ultimately as future partners in building an even broader integrated global system for ex situ conservation resources. Parallel developments in other domains, such as the ZooMu project, which is actively linking data between zoological and museum collections[58], highlight both the feasibility and the value of building bridges between different analogous collections such as living collections and herbaria. Furthermore, the data dimensions illustrated in Fig. 1 parallel those of the extended specimen concept, in which linked data from diverse domains are integrated around a single specimen to create a richer digital object. The living collections community can both contribute to and benefit from the global momentum towards extended specimens, exemplified by emerging initiatives such as iDigBio[40] and DiSSCo[41]. These programmes demonstrate how federated infrastructures can unify heterogeneous data sources at scale, providing a practical pathway for living collections to connect more fully to the wider biodiversity data ecosystem.

In conclusion, living collections have a rich history of adaptation, not only responding to evolving values and needs but also catalysing innovations to address them. In today's era of climate change and accelerating biodiversity loss, with the need for nature-based solutions, the potential of living collections has never been greater. The momentum is evident—from living collections networks to global databases, converging towards a more collaborative, information-rich ecosystem that will enable strategic, evidence-based stewardship of plant diversity on a worldwide scale. Our challenge to our friends, colleagues and community is to come together, to complete this journey to transform our thinking, data practices and information infrastructures. By doing so, we will better position our data, collections and institutions to address the grand challenges of the twenty-first century.

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Additional information
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