TRANSFORMING THE FUTURE OF NATIONAL RESEARCH INFRASTRUCTURE

A DECADAL APPROACH TO AUSTRALIA'S BIOLOGICAL COLLECTIONS

Final Report v1.0, September 2023

Atlas of Living Australia
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Australian Biological Resources Study

CHAH
Council of Heads of Australasian Herbaria

CHAFC
COUNCIL OF HEADS OF AUSTRALIAN FAUNAL COLLECTIONS INCORPORATED

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Citing this publication

Transforming the Future of National Research Infrastructure – A Decadal Approach to Australia's Biological Collections – Final Report v1.0 (2023) A report produced by the Atlas of Living Australia, Australian Biological Resources Study, Council of Heads of Australasian Herbaria, Council of Heads of Australian Faunal Collections and CSIRO. Canberra, ACT pp. 30

Executive summary

Biological (including palaeontological) collections have, for centuries, provided the basis of classical (morphological) taxonomy, been used to catalogue biodiversity, and have been a valuable resource for understanding and managing the effects of environmental change caused by, for example, biodiversity loss and invasive species. Novel techniques in genomics, advanced imaging, machine learning and artificial intelligence, and sampling (for example metagenomic analysis of environmental samples) mean that more information than ever before can be obtained from biological specimens.

The volume, range and demand for expert specimen data are increasing exponentially and smaller niche collections are playing an increasingly important scientific role. Users expect immediate access to specimens and accurate integrated data, for example, biological specimens linked to taxonomic, image, genomic and spatial information. Expanding new uses for biological collections include reference libraries for the identification of environmental DNA (eDNA) samples, biosecurity surveillance, AI approaches to species identification and monitoring, and the discovery of novel molecules and materials. This combination of emerging technologies, science opportunities and policy drivers need a considered national approach to ensure that Australia's biological collections operate in a framework that delivers maximum national benefit.

This decadal approach details what is required to fully realise the benefits of Australia's biological collections as a national research infrastructure. It responds to the recently released National Research Infrastructure Roadmap call for a 'step change' around a national approach to collections, as well as the identification of gaps in related national strategies. These consistently note that despite the growing importance of biological collections to science and decision-making, the lack of a national approach, supported by appropriate resources and partnerships is limiting a fuller realisation of benefits for Australia.

The following five areas that require enhancement underpin the decadal approach:

- Collection digitisation storage, and management
- Digital infrastructure, data access and integration
- Emerging transformational technologies
- Skills and workforce development
- Sectoral leadership

A renewed focus on these key areas will deliver a step change for supporting innovative science in Australia in a diverse range of disciplines spanning biology and geology to materials characterisation and artificial intelligence. This increased support will affect efficient decision-making for government and industry in areas such as biosecurity, conservation, natural resource management, and human health.

1. Introduction

Australia is home to a remarkable and unique biota. Over 70% of our species are estimated to remain undescribed, and over 40% are found nowhere else in the world. Australia's palaeontological heritage is just as unique. Modern biological collections identify and document these unique resources. Biological collections deliver baseline physical and data infrastructure that provides fundamental support to Australian and international research, environmental management, policymaking, and industry.

Physical specimens of living and fossilised species have formed the backbone of biological collections, and novel techniques in genomics, advanced imaging and sampling mean that more information than ever before can be obtained and readily shared from these specimens. The application of new technology unlocks valuable information from old samples across new domains. The concept of a 'digital extended specimen' links physical specimens with data from multiple sources to provide a rich and powerful view of the natural world.

Despite the importance of biological specimens, exponential data increase and the rapidity of technological change, Australia does not have a national approach to managing, resourcing, and governing biological collections but rather has a primarily state-based and funded set of independent institutions.

This decadal approach (the Approach) describes what is needed to fill this gap and augment the fundamental contributions made by biological collections. It is forward-looking, describing five-step changes needed over 10 years to build a national approach to biological collections that will support world-class science and decision-making.

The Approach builds upon extensive national consultation, including the following platforms:

- A national workshop held in May 2023 titled 'Towards a National Approach to Biological Collections' was attended by 65 national stakeholders and thought leaders ('the Workshop').
- A 2023 national survey of needs, priorities, challenges and expected requirements over time, was completed by almost 50 experts and practitioners across Australia ('the Survey').
- Recently completed national strategies and cost-benefit analyses relevant to the biological collections sector (Taxonomy Australia Decadal Plan 2018, Deloitte Access Economics 2020, Atlas of Living Australia Decadal Vision 2022).
- International literature and reviews informing the design of similar global programs (Dasgupta, 2021, National Academy of Sciences 2022, Johnson and Owens 2023).

2. Background

The importance of biological collections has been recognised through strategies including the National Research Infrastructure Roadmap's call for a 'step change' around a national approach to

collections, Taxonomy Australia's Decadal Plan (Discovering Biodiversity: A decadal plan for taxonomy and biosystematics in Australia and New Zealand 2018–2027), the CHAFC National Collection Approach 2021, the National Plant Pest Reference Collections Strategy 2018 and major investments in digitising our biological collections in several major state collections and CSIRO.

In Australia, there has been significant investment nationally in new collections infrastructure within museums, herbaria, and CSIRO, supported by innovative digitisation programs to ensure physical specimens are databased, documented according to international standards and imaged. This investment, however, hasn't covered all of Australia's significant biological collections. When combined with the extant data capability provided by the Atlas of Living Australia, Australia is well placed to harness these digital assets making them accessible nationally, and internationally through the Global Biodiversity Information Facility (GBIF).

Capability and coordination gaps exist across the sector for building a world-class biological collections system. Yet users are rapidly increasing in number and domain driven by innovations in deriving information from biological collections. These uses include providing the sequences for a reference library for the identification of eDNA samples, biosecurity surveillance and AI approaches to species identification and monitoring. Increasingly users expect rapid access to integrated data. These efficient and powerful technological advances present both challenges and opportunities in defining a national approach.

A national approach would parallel international trends, for example, the European Union's Distributed System of Scientific Collections (https://www.dissco.eu/), the largest global formal agreement between natural history museums, botanic gardens, and collection-holding universities. The iDigBio (https://www.idigbio.org/) program in the United States is delivering a similar ambition with a focus on digitisation and data infrastructure.

3. What is a biological collection?

There is no single definition of a biological collection, but different definitions emphasise their contents, management status and/or functions and use.

The following definitions underpin this document:

- **Biological collections** are systematic repositories of biological and palaeontological samples and their associated material and data that are managed as cohesive units in perpetuity and made accessible for use by researchers, industry, and government.
- **Biological and palaeontological samples** include living, preserved or fossilised physical specimens of plants, fungi, animals, and other organisms, including sub-samples such as tissues or blood and characterisation samples derived from, or about such specimens such as DNA, bio-acoustic or image recordings, or mineral samples, and environmental samples such as soils and water that are preserved for research.

- **Associated material and data** include all digital objects derived from or associated with the samples.
- **Managed** indicates that the collection is overtly and actively managed for long-term preservation, access, and research.

These definitions emphasise both the physical and digital nature of collections and their management status. Under these definitions, biological collections do not include databases of unvouchered observational or occurrence records; human and other tissue samples principally used for medical research; zoos, gardens and aquaria maintained principally for display and public enjoyment without a focus on biodiversity research or conservation; and collections of environmental samples that are maintained for purposes other than biodiversity research.

Figure 1 highlights the steps involved in the digital extended specimen (DES) concept from moving beyond the curation and management of physical specimens to creating digital replicas of analogue and physical records and an interconnected network of digital objects globally — "Digital Extended Specimen (DES) network" (Hardisty et. al., 2022) — that transcends existing aggregator technology by augmenting the DES with third-party data through machine algorithms and provides a platform for more efficient research and robust interdisciplinary discovery.

The opportunities created by having a DES include reimagining our collections as a national network of facilities and a national workforce (each embedded in global equivalents) with seamless digital linkages making it possible for a researcher in any single collection to work with and curate and annotate specimens held in any collection. This vision would rely on the conceptual framework represented by DES, but it's much more about how a scattered workforce can become something greater and take shared custodianship for all specimens, including those that are otherwise neglected because there is no relevant taxonomist at a given institution. The DES also provides a vision for turbocharging how collections support can support a modernised taxonomy and leverage images, computer vision, DNA, AI and other tools to deliver the best possible understanding of our biota.

There are several challenges which need to be overcome to move from physical specimens to digital, integrated and linked datasets. For example, it will require development and deployment of new tools, but most of all it will require and drive change in the work practices and work plans across all collections. In its most ideal form, a taxonomist at one collection would have the ability to see all currently digitised information, images, sequences, etc. for every specimen in any collection and would be able to request additional images, sequences, measurements, etc. to be taken by another institution so that these records were complete enough to support development of species concepts. This implies costs for the institution holding the specimen, and these costs may not be fully balanced across the network, so new mechanisms will be required to handle prioritisation and resourcing. Some of the associated costs could be met via the reduced need for travel and loans and via a long-term accounting perspective on the DES as an asset.

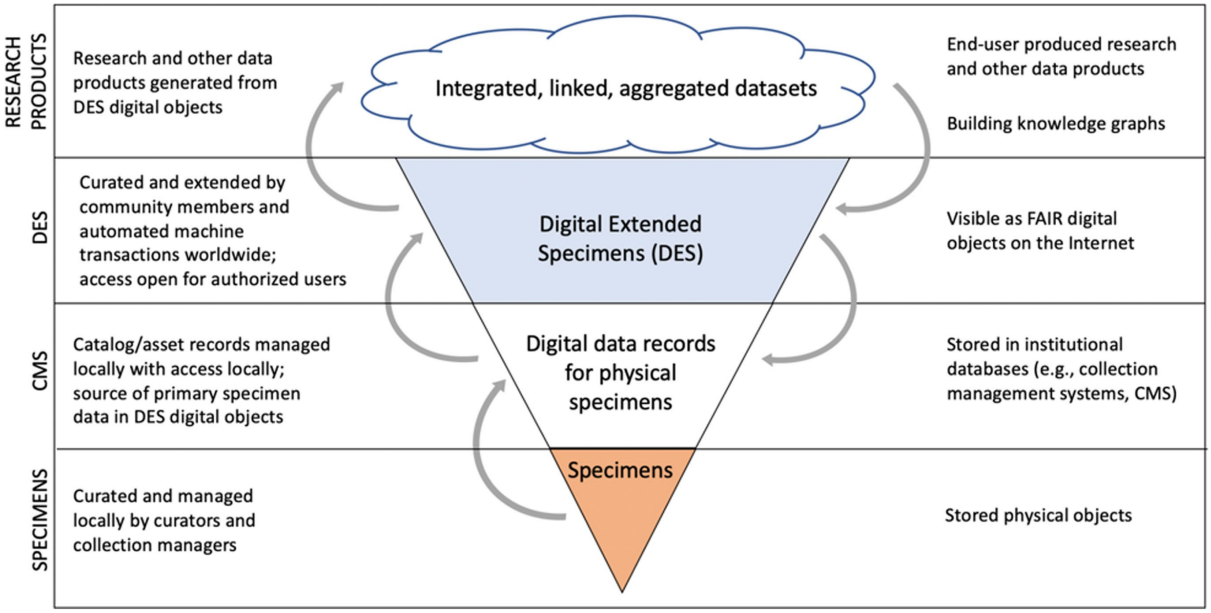

Figure 1 Layers of digital representation beyond physical biological specimens and the data flows between them (Hardisty *et al,* 2022)

4. Drivers and Benefits

The uses of biological collections are varied and changing as technology advances and social and economic needs evolve. Biological collections contribute prominently to the following areas:

- Environmental research, to study biodiversity, evolution, ecology, and a range of other fields.
- Biomedical research, to identify potential new pharmaceuticals and treatments as well as identify emerging vectors and host shifts and track the evolution of diseases.
- Agricultural research, to improve crop yields, develop new plant varieties, and the control pests and diseases.
- Conservation, in which records of species diversity and distribution can be used to monitor changes in biodiversity over time, inform conservation planning, and identify and document rare and endangered species.
- Education and outreach, to provide learning opportunities for students and the public related to biodiversity, evolution, and other foundational biological concepts.
- Biological collections also benefit from and can support First Nations in relation to Traditional Ecological Knowledge, Caring for Country and cultural heritage.
- Biological collections are also important for biosecurity. They are repositories of information that support Australia's pest status and underpin market access and trade outcomes, as well as informing decision-making processes during an emergency response to incursions of exotic pests. Collections provide reference materials (both exotics and native relatives) that are

essential for diagnosticians to accurately identify exotic pests pre and post border to protect our primary industries, the environment and human health. They also provide a source of taxonomically verified source materials which are used to develop effective diagnostic techniques, and other reference materials utilised by diagnosticians (eg. DNA sequences).

The value proposition for national biological collections is multifaceted and encompasses scientific, conservation, biosecurity, educational, cultural, and economic benefits. The recently completed cost-benefit analysis of a mission to discover and document Australia's species Deloitte Access Economics (2021) estimates national benefits ranging between $3.7 to $28.9 billion in one generation. Adopting a national approach to Australia's biological collections would be central to delivering on these benefits. A review of the literature citing collections data (based on ALA records) in Figure 2 shows the breadth of national research that collections-driven research supports - eighteen national research areas (based on Australian Bureau of Statistics research fields). Within terrestrial systems and management, 7% of papers related to taxonomic research and 32% related to biosecurity or threatened species. A recent review of industry use of the ALA (see Figure 3) showed the importance of collection data in driving environmental approvals for natural resource management, infrastructure development and energy projects (over 80% of industry use), while also supporting a diverse array of other industries from horticulture to aviation. Lastly, a similar study on government use of ALA data (Figure 4) shows the importance of collections data across government. While environment department usage comprised around 50% of usage, other users include the Departments of Agriculture (biosecurity), Health and Defence. The Data also showed depth of usage through the three tiers of government, with over 71% of usage by Commonwealth, state, and territory governments and 29% by local government (Figure 4).

Figure 2 National Research Areas (based on ABS research classes) benefiting from a national approach to biological collections based on use of collections for research, 2019-present.

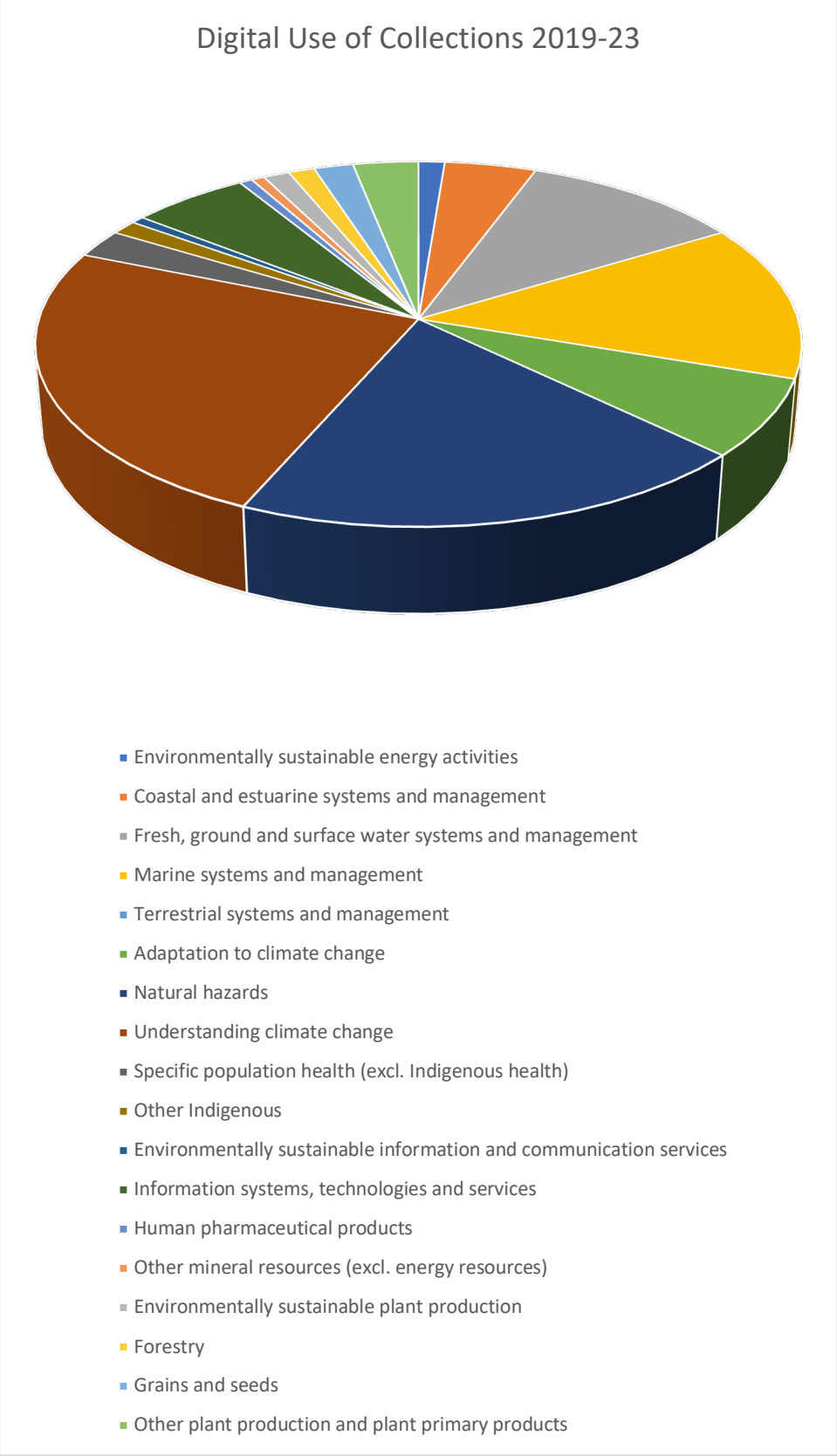

Figure 3 National Industry Sectors benefiting from a national approach to biological collections based on digital usage of collections by industry, 2016-2020

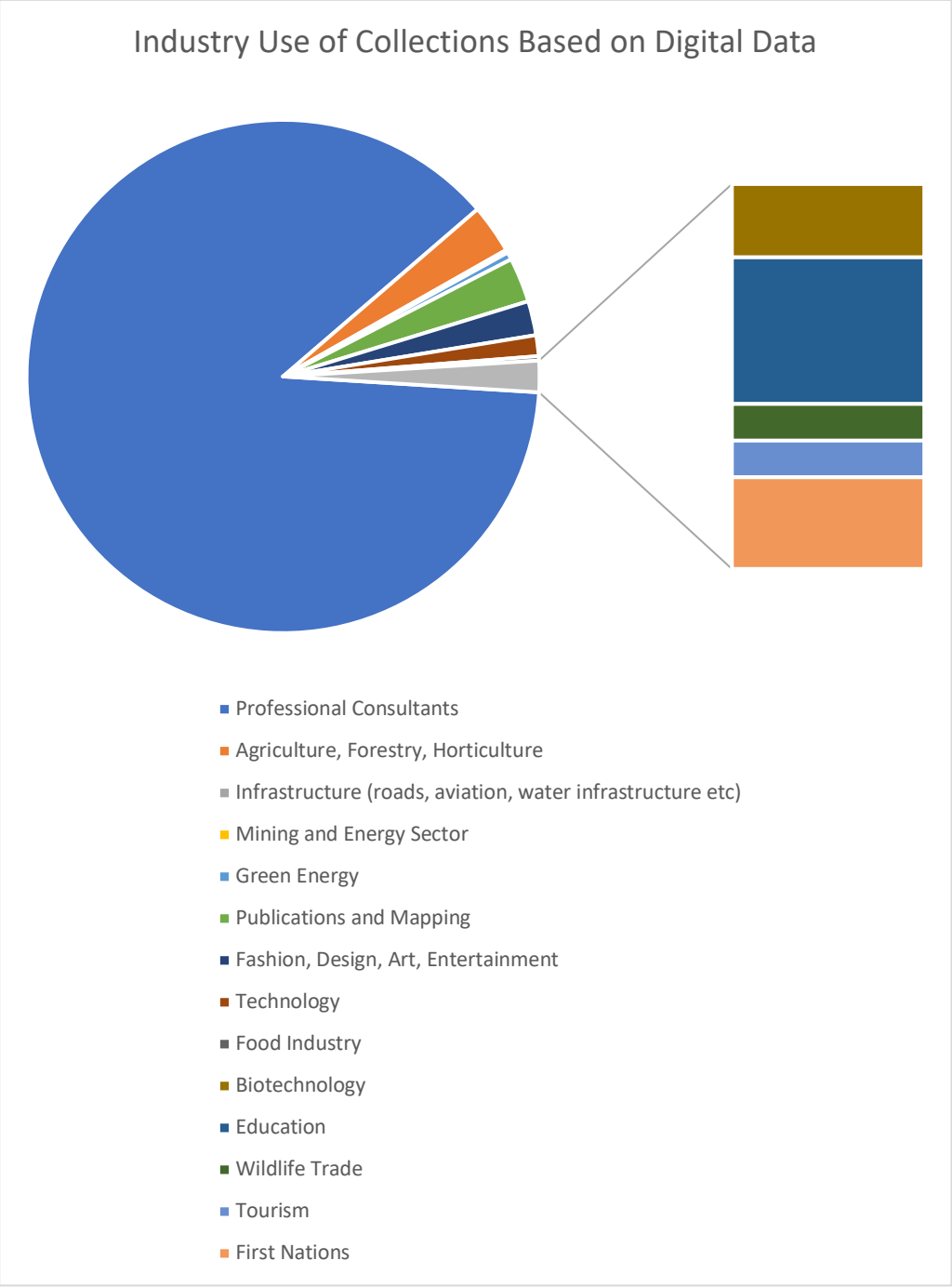

Figure 4 Government benefits from a national approach to biological collections based on use of collections by government 2016-2020

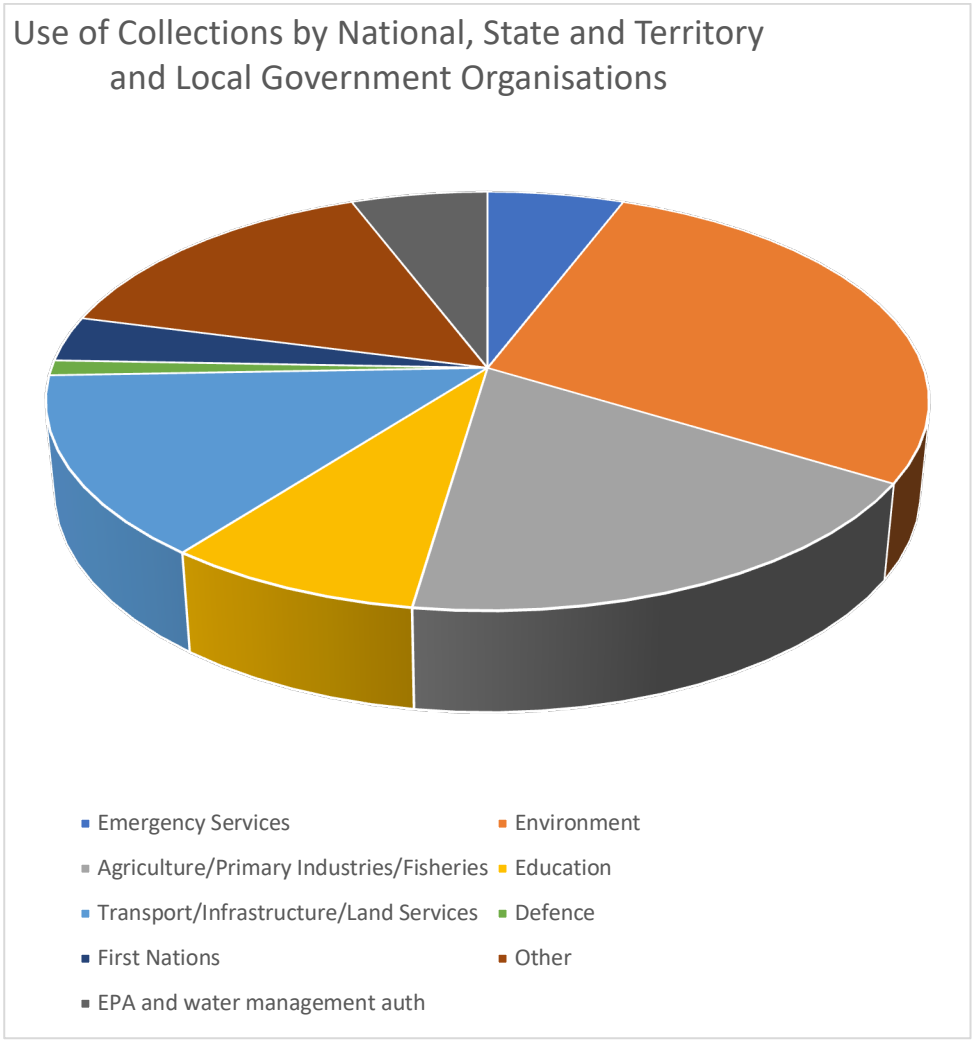

Figure 5 illustrates how biological collections represent a critical resource for understanding the natural world and its important contribution to society and the economy:

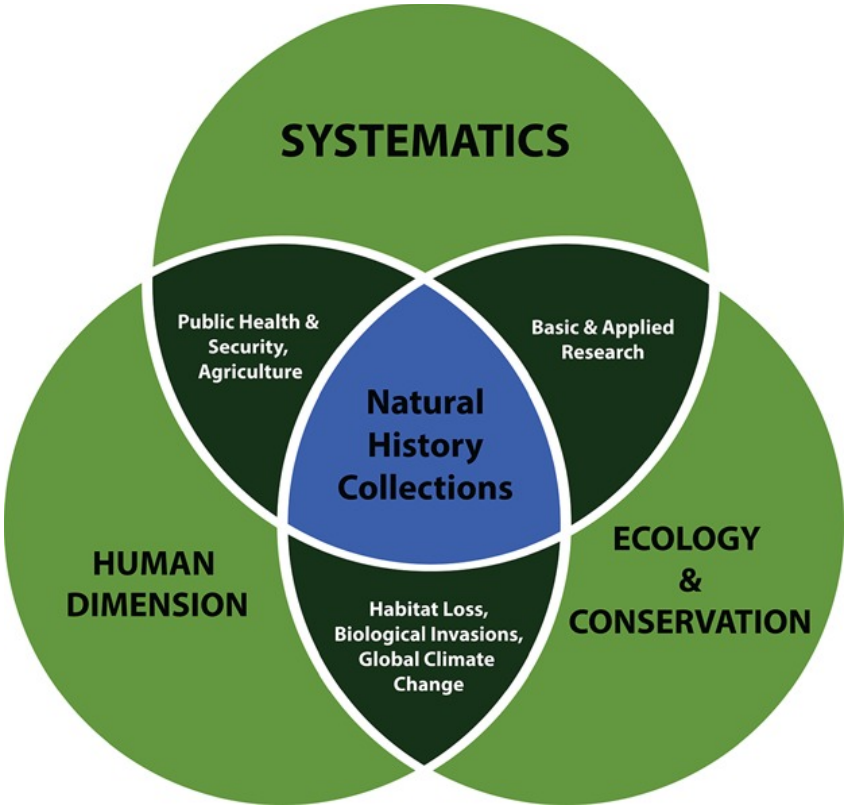

Figure 5 The critical role of biological collections (Wen *et al*. 2015)

There are a variety of different ways to estimate the benefits of biological collections, with the choice depending upon the purpose of the collection and the views of stakeholders. One of the conclusions of a major US study (National Academies of Sciences, Engineering, and Medicine 2020) was that collection specimens can be validated and retain their value to users over time, recognising an important distinction between physical specimens and ephemeral observations or other records that are cannot be validated by a voucher.

5. Current capabilities

Australia has an internationally outstanding network of biological collections managed by state and commonwealth organisations and universities. This includes:

- The state and territory herbaria and museums, university collections, and National Research Collections Australia in CSIRO.
- The biological collections held by Departments of Agriculture and Primary Industries.
- Formal museum faunal collections housed in the university sector.

- The palaeontological collections held by Geoscience Australia and state and territory museums and geological collections.
- Fisheries collections held by Departments of Fisheries and Primary Industries.
- Microbial collections, housed within the university sector.
- Living plant and seed collections held by the major botanic gardens around Australia.

These and related institutions perform the critical functions of housing and identifying and understanding Australia's unique biota as well as exotic specimens that are important reference materials for pest identification and development of diagnostic tools.

Australia has made progress in developing a national approach to biological collections in several areas, including establishing the following bodies:

- The National Collaborative Research Infrastructure Strategy (NCRIS): offering funding and support for national research infrastructure, including initiatives related to biological collections. For example, Atlas of Living Australia (ALA): an NCRIS-funded collaborative digital platform, provides access to biodiversity data from most Australian biological collections, research institutions, and citizen science initiatives.
- The Bioplatforms Australia program, which enables access to advanced genomics, proteomics, and metabolomics technologies able to be applied to the study of biological collections.
- The Australian Biological Resources Study (ABRS): an Australian Government program that supports the documentation, discovery, and classification of Australia's biodiversity through grants, partnerships, and production and maintenance of the National Species list (including the Flora, Algae and Fungi of Australia series and the Australian Faunal Directory).

There is no single national body in Australia specifically focused on biological collections, though the major relevant national bodies are:

- Council of Heads of Australasian Herbaria (CHAH) is a collaborative peak body that brings together the directors and managers of major herbaria in Australia and New Zealand. Its main objectives include promoting the use and development of herbarium collections, coordinating collaborative projects, and advocating for the interests of herbaria in the region. CHAH has overseen projects such as the development of the Australasian Virtual Herbarium, which provides online access to herbarium specimen data from across the region.
- Council of Heads of Australian Faunal Collections (CHAFC) is a collaborative peak body that represents the interests of the major fauna collections held at state, territory and commonwealth level. The CHAFC aims to promote the value of faunal collections, facilitate collaboration among institutions, and advance the management and use of these collections for research, education, and conservation purposes. CHAFC plays a crucial role in coordinating efforts related to faunal collections in Australia.

- Council of Australasian Museum Directors (CAMD): The CAMD is a collaborative committee that brings together the directors of major museums in Australia and New Zealand. While not exclusively focused on biological collections, CAMD provides a platform for museum leaders to discuss common issues, share best practices, and advocate for the importance of museums in research, education, and public engagement.
- The collections committee of the Australian Entomological Society represents national entomological collections, including significant biosecurity collections held by the Departments of Agriculture and Primary Industries
- The Reference Collection Implementation Plan Working Group which reports to the Subcommittee on Plant Health Diagnostics oversee the implementation of the National Plant Pest Reference Collections Strategy which includes recommendations and actions relating to coverage, standards, accessibility and coordination.

Other bodies and networks, including Taxonomy Australia, support collaboration among taxonomists and institutions, including museums and universities, and advocate for the importance of biological collections and taxonomy in understanding and preserving Australia's biota.

6. Emerging Challenges and Opportunities

A survey of the biological collections sector's needs, priorities, challenges, and changes over time was completed in April 2023 by some 46 experts and practitioners across Australia and informed the May 2023 national Workshop. Together, the survey and workshop formed an important basis for this report and to develop a national approach to biological collections which supports world-class science and decision-making.

The survey results provide the most up-to-date and authoritative overview of the needs and opportunities for the sector. The top priority national needs for biological collections are clustered into four themes:

- Digitisation, data/documentation infrastructure
- Advanced imaging and -omics infrastructure
- Skills and workforce development
- Provision of baseline information

The experts and practitioners concluded that the need for each of these priorities will increase over time, as indeed will all priorities across the board. It is expected that there will be increasing emphasis on extended specimens and meta collections; genomics, molecular analysis; and big data. Emerging challenges were identified in relation to the increasing demand for destructive sampling of finite specimen resources, and poor funding and cutbacks to collection management.

There were also immediate concerns with serious issues including those relating to the valuation of collections to enable their recognition and management as assets; failing collections management systems; resourcing the availability of collections to external users; and lack of / poor physical storage and maintenance.

The Workshop elaborated on these challenges and opportunities, noting:

- The general lack of understanding by users, funders and decision-makers of the value and contribution of biological collections to research, policy and decision making and industry.
- A lack of appreciation within government for what is required to maintain biological collections effectively.
- Opportunities to enhance coordination and interconnection among and between collections, including in relation to access and loans, standards, and technology.
- The maturity of the sector means that it is feasible to form a national body or partnership and coordination mechanism specifically focused on biological collections to better coordinate nationally across the various collections in state and federal government, museums, herbaria, and universities.
- Challenges and opportunities related to skills and workforce development.
- The promise of new technologies, the need to increase access to existing facilities, and the need for skills and systems to increase their use.

Together, the growing importance of the sector, the pace and scale of change and the growth in user expectations obviate the need for a step change.

7. Themes supporting a decadal approach

To achieve a national approach to biological collections, the following themes were identified.

- Collection digitisation, storage and management
- Digital infrastructure, data access and integration
- Emerging transformational technologies
- Skills and workforce development
- National coordination

The list is high-level and aspirational. It aims to achieve step changes in the effectiveness, efficiency and value delivered by the sector, focussed not upon smaller incremental changes or a better version of business as usual.

7.1 Collection digitisation, storage and management

Collection growth

- Some 70% of Australian species are not described or are new to science (Taxonomy Decadal Plan Working Group, 2018). New technology, including imaging, tissue and DNA sampling and AI, can accelerate and deepen how rapidly new species are described, but only with substantial growth and investment in skills, training, and capacity (including both in the taxonomic, collections and research workforces) as well as better access to existing facilities and new investment.
- New technology, in common with traditional identification practices, depends upon agreed taxonomies and standards for describing specimens in biological collections and managing the associated taxonomic data. The ABRS National Species List forms the centrepiece of this but further work remains to be done, in relation to taxonomy and other curatorial issues.
- New forms of data are being created and collected. Camera traps, genomic data including eDNA, soundscapes and other forms of data are growing rapidly and require storage, curation, and analysis.
- There is also a growth in databases and database needs, including biosecurity and agriculture-related products such as the Australian Plant Pest Database (APPD), which sit outside major herbaria and museums (and other national collections) which have not necessarily been considered as part of the biological collections network in Australia. There is an opportunity to work with such collections to form a more inclusive approach to biological collections.

Digitisation

- Australia has made considerable progress on the digitisation of its biological collection specimens but much more remains to be done including resourcing staff in this area. This is critical to enhance access to information, facilitate research and conservation efforts, and preserve the collections for future generations.
- Bioplatforms Australia supports advanced genomics, proteomics, and metabolomics technologies that can be applied to the study of biological collections. These technologies enhance the digitisation process by generating new types of data, such as genomic or molecular information, to complement traditional specimen data. Further resources are needed to exploit the potential of the 'digital extended specimen' concept and expand genetic resource libraries. The need for resourcing includes the need for a skilled workforce to taxonomically validate specimens if they are to be sued to generate these new types of data.

Collection management

- A variety of collection management systems (CMS) are used in Australia to manage, organise, and maintain biological collections. The choice of a CMS may depend on the size of the

institution, the types of collections, the available resources, and the specific needs of the organisation. Challenges include aging infrastructure in some large collections, the difficulty in intersecting CMS with aggregator systems and biological collections, particularly small collections, may not have internal expertise or resources for a fully maintained CMS.

- Physical storage. Every Australian biological collection is at or over capacity. Aging infrastructure means many collections are threatened by mould and pests, power outages, inappropriate Australian standards (such as those for wet collections) designed for other sectors and a host of other issues. These very significant challenges highlight the need to improve and expand the storage for normal specimens, many of which are housed under poor archival conditions and the very large challenge of accommodating the emerging new kinds of collections such as tissues, blood and DNA that need specialised storage in terms of large-scale biobank facilities. These biobanks also require specialised support from qualified technicians. Most museums are under-resourced for the management of these valuable and collections.
- The Australasian Virtual Herbarium (AVH) is an online resource that provides dynamic access to plant specimen data as Online Zoological Collections of Australian Museums (OZCAM) does for fauna. Both these are heavily dependent on the ALA. There is no single capability to access information on the full range of biological collections and specimens. While the ALA provides for specimen discovery, there is no single current capability that can offer an annotation service, links between specimen duplicates, or discover sample locations.
- Australia's biological collections may benefit from implementing a consistent approach to specimen valuation practices. This would ensure harmonisation across the sector, leading to a consolidated figure representing the total value of the National Biological Collections Asset.
- A particular issue in the management of biological collections is the relationship between First Nations people and traditional knowledge. Most of Australia's biological collections actively engage with First Nations people, and there are important ongoing agendas related to traditional ecological knowledge; the cultural significance of collections for First Nations communities; informed consent and protocols for access and benefit-sharing; collaborative research and more.
- Other research infrastructure capabilities have centralised portals to enable access or use. In Europe DiSSCo is aiming to synthesize access across over one hundred collecting institutions. Such a concept would potentially be valuable in Australia to streamline visits, request specimens and organise loans.
- Strengthening Australia's collection management system will provide benefits to the broader network of collections in the Asia-Pacific through proactive engagement.

7.2 Digital infrastructure, data access and integration

Digital infrastructure

- High-quality imaging equipment, such as cameras, scanners, and microscopes, are needed to capture detailed digital images of specimens, and technologies such as 3D scanning, genomic sequencing, and molecular analysis can generate complementary data. There are resources available within Australia that could be used by biological collections though more work may be needed to enhance access with state, territory, and national initiatives.
- Reliable, secure, scalable data storage solutions ensure the long-term preservation and accessibility of digitised specimens, advanced imaging, genomics, and associated data. There may be scope for consolidated national approaches to digital storage solutions to create "value for money" discoverable approaches and logical containerisation of data for end users from researchers to the public.

Data access

- Data-sharing platforms such as the Atlas of Living Australia (ALA), AVH, APPD and OZCAM play a crucial role in aggregating and providing access to biological collection data. Continued development and support of these platforms, as well as a contribution by biological collections (including smaller collections or those from related domains), is necessary to facilitate data access, sharing and collaboration.
- Institutions have varying policies regarding data access and sharing, which can create inconsistencies and barriers to collaboration. Encouraging the adoption of standardised policies for data access can facilitate more effective data sharing and reuse. The experience of the Restricted Access Species Data project shows the value of developing national best practices in data protocols for (for example) the locations of endangered species or culturally significant materials.
- Navigating complex legal and ethical frameworks, such as the Nagoya Protocol on Access to Genetic Resources and Benefit-sharing or national legislation on the collection and use of biological materials, can pose challenges for data access and sharing. Ensuring compliance with these frameworks while promoting open access is crucial for responsible data management.

Data integration

- Australia is likely for the foreseeable future to maintain a distributed approach to data integration, building upon the strengths of individual institutions and combining to provide seamless access for users. Achieving this will require collaboration and coordination, data and metadata standards including agreed national taxonomies, FAIR (Findable Accessible Interoperable Reusable) and indigenous CARE (Collective benefits, Authority to control, Responsibility and Ethics) data, and oversight to help guide continuous improvement in data integration.

7.3 Emerging transformational technologies

Several new technologies are fundamentally reshaping what science can be conducted using biological collections specimens, the kinds of data that can be extracted from them and the applied outcomes they can generate.

- 'omics-based science including genomics, transcriptomics, museomics (Gaulthier *et al* 2023) and proteomics. The rapidly improving ability to extract omics information from preserved specimens is providing data that will make collections the most comprehensive genetic libraries of Australia's unique biodiversity. These libraries can be used as reference data to interpret eDNA biomonitoring of biodiversity and surveillance of pests' or biodiversity, discover new species, search for useful molecules and materials and identify invasive species, disease vectors and infection pathways.
- Machine learning and artificial intelligence. The application of AI to collections specimens as training data sets for machine learning is generating unique new tools for the identification of species that can be used to monitor the environment as well as provide reliable identification tools for biosecurity applications. The opportunities to undertake digital trait extraction is beginning to allow the use of collections to track phenological responses of key species and communities to environmental change and make predictions about future trajectories for Australia's ecosystems. AI can also be used to improve the efficiency of curator operations around some basic tasks such as public identifications.

7.4 Skills and workforce development

Australia's biological collections community experiences common challenges in relation to workforce development, leading to the following priorities:

- Recruitment, capacity building and training (non-tertiary solutions) to ensure that staff supporting the research infrastructure represented in collections have the necessary skills and expertise to undertake both collection management and taxonomy.
- There are limited career pathways available in biological collections in Australia. Providing clear career pathways and opportunities for advancement will increasingly be needed to help attract and retain qualified professionals and encourage long-term commitment to the field of biological collections. A crucial issue is that much of the workforce shortage is hidden by the massive gratis contribution of volunteers, research associates and fellows in institutions across Australia. There may be opportunities to develop a national approach to career pathways, offering a diversity of opportunities and career advancement pathways.
- Skill gaps, driven by limited employment opportunities and exacerbated by skills demand because of the rapid advancement of digital technologies, genomics, and artificial intelligence.

- Ongoing training and professional development opportunities for current staff is vital as is the role of new recruitment in terms of re-shaping the collections workforce to embrace the opportunities of the future that will maximise the national value of collections for Australia.
- Tertiary Training. Currently, no university in Australia offers a degree in taxonomy or biological collection management. There may be the opportunity to develop a degree course, as well as modules and micro courses, accredited by one or more universities, and offered across the sector. The target market for this may include environmental impact assessment staff as well as those employed in biological collections. There are models to be explored in the European Union.
- The integration of traditional and First Nations knowledge with biological collections poses challenges and opportunities in relation to staff skills. Ensuring that the workforce is equipped with the knowledge and skills to work with First Nations communities to appropriately integrate traditional and First Nations knowledge into collection management, research, and conservation practices will require additional workforce development.
- There is the opportunity to explore opportunities for a virtual taxonomy and biological collections workforce, with skills available in one institution available to others, and with the possibility of staff exchanges and placements.

7.5 National coordination

There is no single national body in Australia specifically focused on the management and coordination of the biological collections sector. The opportunity exists for such a body, or partnership/coordination mechanism, to advance the coordination and management according to a national agenda and to enhance the ability of the sector to meet user needs.

In the shorter term, these functions could be advanced by a modified form of the organising committee for the Workshop, 'Towards a National Approach to Biological Collections'. This group comprised Atlas of Living Australia, Australian Biological Resources Study (ABRS), Council of Heads of Australasian Herbaria (CHAH), Council of Heads of Australian Faunal Collections (CHAFC) and National Research Collections Australia (CSIRO). Adding interests representing biosecurity, microbial, and palaeontological collections could round out national representation.

Over time a partnership or coordination Biodiversity Hub mechanism with coordination responsibilities could be developed to pursue national management of biological collections. It could be supported by a contribution from a central fund such as NCRIS and supplemented by contributions from organisations across the biological collections sector. A central body could be supported by a 'Biological Collections Action Centre', a small body focussed on the delivery of the promise of a decadal approach.

There are several issues that could be advanced through greater sectoral coordination, including:

Outwards beyond the biological collections sector:

- Elaborate and promote the value proposition of a nationally distributed and connected approach to biological collections to stakeholders including First Nations people and potential partners.
- Provide centralised national management based on the value proposition to users.
- Promote a seamless user experience across biological collections between NCRIS Facilities, state, territory, research, university, government and industry organisations.
- Develop a strategy that prioritises the study of Australian taxonomic groups that are poorly known.

Within the biological collections sector:

- Articulate principles to underpin how the sector can work together and deliver ever-stronger value to users.
- Pursue productivity increases and improved national systems (e.g., for valuation, specimen loans or digital specimen access) to achieve economies of scale and facilitate access to emerging technology.
- Develop an impact tracking system to provide ready information on how biological collections are used and by whom. Develop systems to measure the impact of the sector upon users and metrics to demonstrate the benefits of national approach.
- Develop 'star' ratings for biological collections, to help create incentives for further development and targeting of limited resources across a range of competencies including the issues identified in this document.
- Organise cross-sectoral and professional activities such as collection management working groups that build on current bodies such as the Herbarium Information Standards Committee (HISCOM) and Fauna Collections Information Group (FCIG) to encourage a national approach to management; oversight mobility opportunities and establish the development of sectoral national standards (aligned with international standards as they are developed).

The role of NCRIS is critical in enabling collaborative national leadership.

Proposed Roadmap – Decadal Approach to Australia's Biological Collections

Themes	Immediate term (1-3 years)	Medium-term (3-5 yrs)	Success in 10 years
Collection growth, digitisation, and management	• Accelerate species discovery. • Ensure gaps in coverage of priority exotic specimens are addressed • Investment in diagnostics, tools, systems and workforce • Work with linked domains, including biosecurity and agriculture, to broaden approach to biological collections. • Agreed methods to value collections. • Deepen relationship with Indigenous people and traditional knowledge.	• Maintain taxonomies & standards. • Interoperable collection management systems	• Double the current proportion of Australia's species that are described. • Up to date taxonomies and standards • Adequate infrastructure to house collections • Increased digitisation of collection and improved currency of information
Emerging transformational technologies	• Investment in tissue banks • Protocols for digital data capture that are machine learning friendly. • Develop national collection-based DNA Sequence reference libraries	• Consolidated tissue bank infrastructure • Protocols in place for AI friendly digital data capture • DNA reference sequences available for majority of Australian metazoan species and potential invasive species.	• National tissue bank operational and supporting research and environmental management • Digital collections in AI friendly format • DNA reference sequence available for all Australian species
Digital infrastructure, data access and integration	• Enhance access to high-quality imaging equipment. • Investment in digital storage • Protocols for access to sensitive data • Standardised policies for data access & sharing • Compliance with frameworks for collection & use of biological materials • Agreed national standards. • Single comprehensive access portal for specimen data	• Consolidated digital storage solutions. • Enhanced data integration, data & metadata standards including FAIR data & oversight.	• Digital extended specimen architecture operational • Seamless user experience across biological collections through single portal
Skills and workforce development	• Forming the virtual biological collections workforce • Investment in taxonomy and collection skills • Pilot training and professional development approaches • Training to integrate traditional and Indigenous knowledge into collections, research, and conservation practices	• Degree, module and micro-level courses, accredited by one or more universities, and supported by increased grant support.	• Dynamic, highly trained workforce with attractive career pathways
Sectoral leadership	• Organising committee for the Workshop to promote this Roadmap • Form a body, or partnership / coordination mechanism, and create a 'Biological Collections Action Centre', to deliver this decadal approach	• Metrics to demonstrate benefits of national approach.	• Clear sector identity and voice, based upon the value proposition to users. • Identifying ongoing sustainable funding mechanisms to support collections nationally

8. Strategic alignment to the NRI roadmap

The Australian Government issues a National Research Infrastructure Roadmap every five years. The 2021 Roadmap provides the best single overview of Australia's research infrastructure needs, and funding under the roadmap continues to support critical capacity within Australia's biological collections sector. This decadal Approach maps closely to the aspirations of the 2021 National Research Infrastructure Roadmap including against the following roadmap themes:

Research themes, challenges and NRI impact: Environment and climate

- The roadmap outlines that research to safeguard future prosperity against environmental and climate threats should be underpinned by the following research infrastructure:
    - Biodiversity monitoring, collection, and analysis infrastructure
    - Integrated, publicly accessible environmental datasets.

Opportunities for system-wide enhancements in NRI: physical collections and biobanking

- The roadmap notes that physical collections of specimens and taxonomy are critical to support the identification of biosecurity risks and determine action, supporting Australia's environmental and climate adaptation strategy. It identified issues including:
    - Metadata capture and standards to ensure that data are findable and accessible, interoperable across institutions and platforms and to address current disparity in discoverability, accessibility, and quality of data.
    - Evolving analytical technologies (genomics, imaging, digitisation etc.) which are generating new opportunities for specimen and sample use and reuse.
    - Open access infrastructure, involving the development of unified sample management systems, metadata protocols, consistent access models and shared data infrastructure. These technologies can also help manage the finite resources of biobanks.
    - The need for a skilled workforce and expertise to support physical collections and biobanking, including in the curation and preservation of collections.

Potential for step-change: A national approach to collections

- The NRI Roadmap notes that a scoping study will help understand the potential opportunities that arise from taking a national approach to collections, including networking, and leveraging existing investments and assessing the emerging capability needs and technology platforms.
    - Overall, this study responds to the issues identified in the roadmap and describes four-step changes needed over 10 years to build a national approach to biological collections that will support world-class science and decision-making.

- It is an input into a larger scoping exercise being undertaken by the Australian Academy of Science.

Table 1 outlines how the five enhancements in the decadal approach will contribute directly to the vision articulated in the 2021 National Research Infrastructure Roadmap.

Table 1 Alignment between biological collections proposed enhancements and key themes in the National Research Infrastructure Roadmap

Proposed Enhancements	**Through New Investment**	**National Research Infrastructure Roadmap**
Collection growth, digitisation, and management	By doubling the mobilisation of collections-based biodiversity data linked to stored specimens, developing national standards, and improving digital taxonomies, the Approach will achieve a step change in biodiversity monitoring, collection and analysis infrastructure and the provision of integrated, publicly accessible environmental datasets. By providing targeted investment in new technologies such as improved tissue banking facilities, improved imaging and metadata capture facilities within the distributed national system, and improved data and collection storage facilities the Approach enables the Sector to respond to emerging demands over the next ten-year period.	Challenges: Environment and climate
Emerging Transformational Technologies	By establishing a national DNA sequence library and extending collection discoverability to AI, the Approach will achieve a step change in aligning collections with emergent needs in research, policy and management and underpin Australia's responses to environmental challenges and climate.	
Digital infrastructure, data access and integration	By delivering a common approach across biological collections to the 'digital extended specimen', and a seamless user experience across biological collections to access 'digital extended specimen' data through single portal – this will achieve a step change in metadata capture and standards, FAIR data, the use of new technologies (genomics, imaging, digitisation etc) for specimen and sample use and reuse, and open access infrastructure.	Opportunities for system-wide enhancements: Physical collections and biobanking
Skills and workforce development	By fostering a dynamic, highly trained workforce in collections and taxonomy with attractive career pathways, this will ensure a skilled workforce with expertise to support physical collections, diagnostics and biobanking, including in the curation and preservation of collections and identification of specimens.	

Proposed Enhancements	Through New Investment	National Research Infrastructure Roadmap
National leadership	By providing a clear sector identity and voice, based upon the value proposition to users, this will achieve a step change in the national approach to biological collections.	Step change: A national approach to collections

9. Conclusions and next steps

Considerable capability and infrastructure exist across Australia's biological collections sector, particularly regarding the larger institutions that play a critical role in biodiversity discovery, identification and description, digitisation and in supporting cutting-edge science. Currently benefits from our biological collections are realised across many sectors including science, industry, government, and in support of public programs. However, our nation's smaller collections don't have equal access to people, infrastructure, and technology, while emerging science uses in domains such as evolutionary biology, taxonomy, genomics and conservation biology demand a more integrated national system. Ultimately 70% of Australia's unique species are estimated to remain undescribed and / or undiscovered, a situation which significantly limits both science and conservation outcomes. Improving our understanding of Australia's biota would in parallel deliver benefits to the economy and society for example by delivering benefits to the biosecurity and agricultural sectors.

A more integrated national system would see a step-change in (a) collection digitisation, storage, and management, (b) digital infrastructure, data access and integration, (c) supporting emerging transformational technologies, (d) enhancing skills and workforce development, and (e) sectoral leadership. Australia's biological collections are well placed to partner to deliver a more integrated national research infrastructure given both organisational and technical maturity. Importantly for Australia's science community, additional momentum would allow Australia's science community to collaborate internationally with similar programs particularly in Europe and the US. There also remains a pressing regional opportunity for greater leadership in and benefits to the Pacific and parts of Asia which are similarly challenged. The biodiversity science and management challenge is global in scope. Rapid access to international expertise, data and transformational technologies and establishing sovereign capability in Australia is fundamental in enabling global partnerships.

This report has leveraged the learnings from earlier reviews and programs in Australia, and findings from a national workshop held in 2023 and the supporting national survey of needs, opportunities, and future science drivers. The next step in this process is to share these findings with the Australian Academy of Sciences who are leading a broader review of needs and priorities. A parallel process led by a working group with representation from the ALA, ABRS, CHAH, CHAFC and CSIRO will develop a business case with more detailed costings to deliver each of the 5 proposed enhancements under multiple scenarios. Co-investment and partnerships will be fundamental in supporting the enhancements and the working group welcomes further discussions with stakeholders keen to be formally involved in the nascent program. Australia's biological collections are uniquely placed to deliver greater science and applied benefits through the delivery of the enhancements proposed in this report.

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Appendix A

Organisations and institutions contributing to May 2023 National Workshop

Atlas of Living Australia
AuScope
Australian Academy of Science
Australian Access Federation
Australian Antarctic Division
Australian Entomological Society Collections Committee
Australian Museum
Australian National University
Australian Research Data Commons
Australian Tropical Herbarium
BioPlatforms Australia
Charles Darwin University
Commonwealth Scientific and Industrial Research Organisation
Curtin University
Department of Agriculture, Fisheries & Forestry
Department of Biodiversity, Conservation and Attractions
Department of Biodiversity, Conservation and Attractions - Western Australian Herbarium
Department of Climate Change, the Environment, Energy & Water
Department of Education
Department of Environment and Water, South Australia
Department of Primary Industries, NSW
Flinders University
Geoscience Australia
La Trobe University
Mia Swainson Consulting
Museums Victoria
National Imaging Facility
Office of Threatened Species Commissioner
Phenomics Australia
Queensland Department of Agriculture and Fisheries
Queensland Herbarium
Queensland Museum
Royal Botanic Gardens and Domain Trust
Royal Botanic Gardens Victoria
South Australian Museum

Tasmanian Museum and Art Gallery
Taxonomy Australia
Terrestrial Ecosystem Research Network
University of New South Wales/Managers of Australasian Herbarium Collections

University of Sydney