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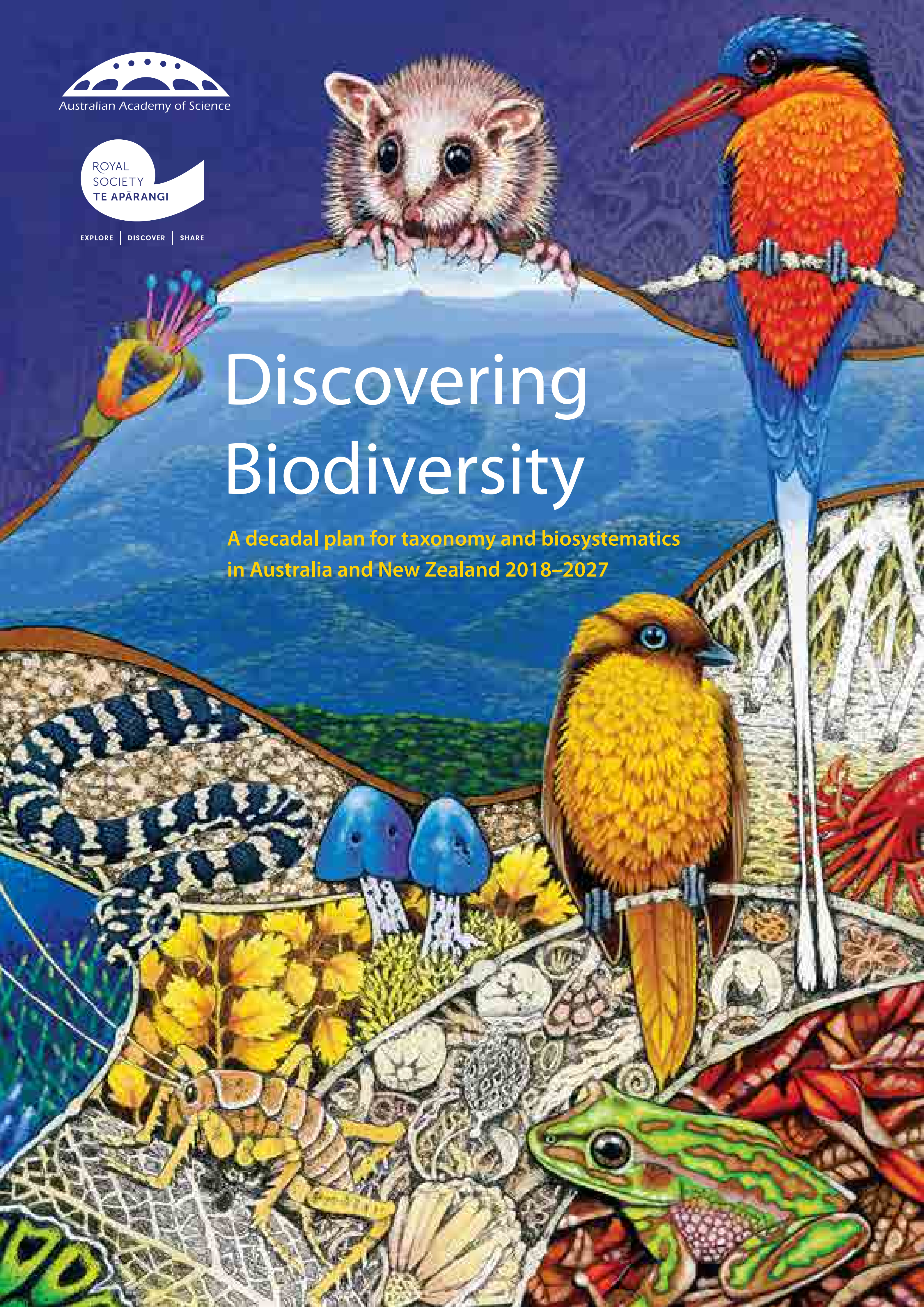
Discovering Biodiversity

A decadal plan for taxonomy and biosystematics in Australia and New Zealand 2018–2027



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AUSTRALIAN ACADEMY OF SCIENCE | ROYAL SOCIETY TE APĀRANGI | APRIL 2018

Acknowledgements

This decadal plan was developed with funding from the Ian Potter Foundation, and funding or in-kind support from the following partners:

The Council of Heads of Australasian Herbaria (CHAH)
The Council of Heads of Australian Faunal Collections (CHAFC)
The Australasian Systematic Botany Society (ASBS)
The Society of Australian Systematic Biologists (SASB)
The Australian Biological Resources Study (ABRS)
The Atlas of Living Australia
The Commonwealth Department of Agriculture and Water Resources
National Research Collections Australia, CSIRO
The University of Adelaide
CSIRO Publishing
GNS Science
Manaaki Whenua – Landcare Research New Zealand
National Institute of Water and Atmospheric Research
Auckland War Memorial Museum
Canterbury Museum
Museum of New Zealand Te Papa Tongarewa
Massey University
University of Otago

It was developed under the auspices and with the support of the Australian Academy of Science and New Zealand's Royal Society Te Apārangi.

Its development would not have been possible without substantial support and contributions from members of a Working Group and Advisory Committee, members of which are listed in Appendix 1.

Finally, it would also not have been possible without the contributions, vision, patience, good will, and constructive feedback of the entire taxonomy and biosystematics community, and of the community's many stakeholders and end users, in Australia and New Zealand.

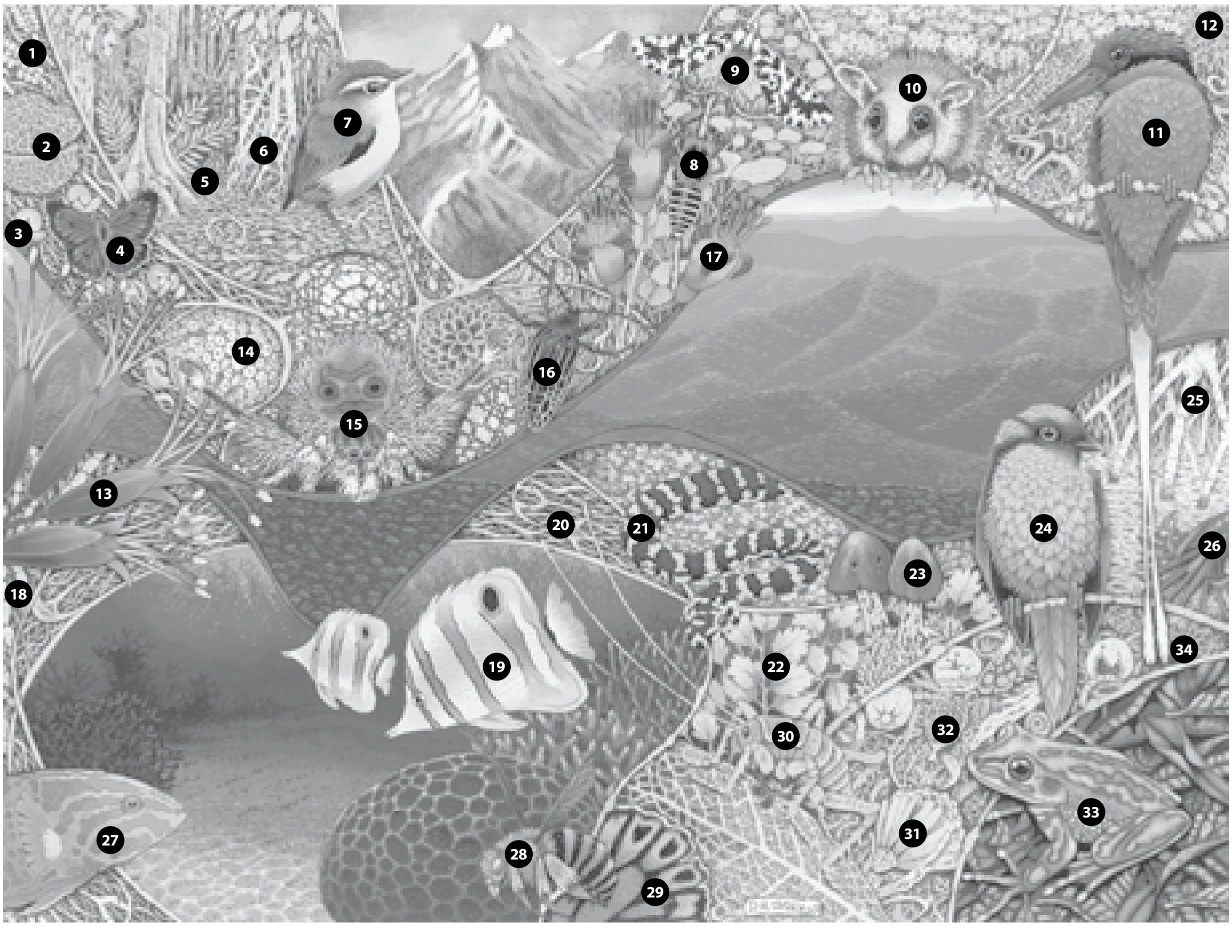
The Ian Potter Foundation

ISBN 978 0 85847 593 9

Prepared by the Decadal Plan Working Group
on behalf of the Australian Academy of Science and the Royal Society Te Apārangi.

Cover image: *Abundance* by David Stacey
Foreword portrait image: Department of Foreign Affairs and Trade CC BY 3.0 AU via Wikimedia Commons

Cite this plan as: Taxonomy Decadal Plan Working Group (2018). *Discovering Diversity: A decadal plan for taxonomy and biosystematics in Australia and New Zealand 2018–2028* (Australian Academy of Science and Royal Society Te Apārangi: Canberra and Wellington)



1. An un-named fungus, possibly an Atractiellomycete
2. A dinoflagellate, *Protoceratium reticulatum*
3. An un-named basidiomycete fungus
4. Boulder copper, *Lycaena boldenarum*
5. Rainforest understory
6. Strangler fig, *Ficus destruens*
7. New Zealand rock wren, *Xenicus gilviventris*
8. Two-lined gum leafhopper, *Eurymeloides bicincta*
9. North Island zebra moth, *Declana atronivea*
10. Feathertail glider, *Acrobates pygmaeus*
11. Buff-breasted paradise-kingfisher, *Tanysiptera sylvia*
12. Cloud forest
13. New Zealand flax, *Phormium tenax*
14. Vegetable sheep, *Raoulia mammillaris*
15. Coastal peacock spider, *Maratus speciosus*
16. Huhu beetle, *Prionoplus reticularis*
17. Creeping Fuchsia, *Fuchsia procumbens*
18. Neptune's necklace, *Hormosira banksii*
19. Beaked Coralfish, *Chelmon rostratus*
20. A dinoflagellate, *Ceratium* sp.
21. Darwin carpet python, *Morelia spilota variegata*
22. Beech leaves, *Nothofagus* sp.
23. Purple pouch fungus, *Cortinarius porphyroideus*
24. Golden bowerbird, *Prionodura newtoniana*
25. Mangrove forest
26. Section of Mangrove fruit
27. Moon Wrasse, *Thalassoma lunare*
28. Blue-banded bee, *Amegilla cingulata*
29. Cairns birdwing, *Ornithoptera euphorion*
30. Stephens Island weta, *Deinacrida rugosa*
31. Bark section of a grass tree, *Xanthorrhoea johnsonii*
32. Fruit of *Casuarina*
33. Green and golden bell frog, *Litoria aurea*,
34. *Dillenia* flower

Abundance

This artwork celebrates the rich tapestry of nature and the beauty of all things. Nature to me is true and steadfast, it needs no alibi for its existence for it is ethereal.

— D.H. Stacey

A leopard anemone (*Antiparactis* sp.) from Rangitāhua Kermadec Islands. A lack of suitable taxonomic expertise in New Zealand and Australia means that this spectacular species cannot be accurately identified.

CREDIT: RICHARD ROBINSON

The channel between Hook Reef and Hardy Reef, Great Barrier Reef Marine Park. The Great Barrier Reef is one of the richest and most diverse biomes on Earth.

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Litoria bicolor. The tree frog genus *Litoria* is widespread throughout Australia. Ongoing taxonomic research is revealing many new species, especially in northern Australia. *Litoria bicolor* itself probably represents several undescribed species.

CREDIT: JODI ROWLEY / © AUSTRALIAN MUSEUM

Scope of this plan

In this plan, biodiversity is understood to comprise all species (and other taxa) of organisms, both native and introduced, living and fossil, and the genetic and evolutionary diversity that characterises them. This includes all marine, freshwater and terrestrial plants, animals, fungi and microorganisms, including bacteria and viruses.

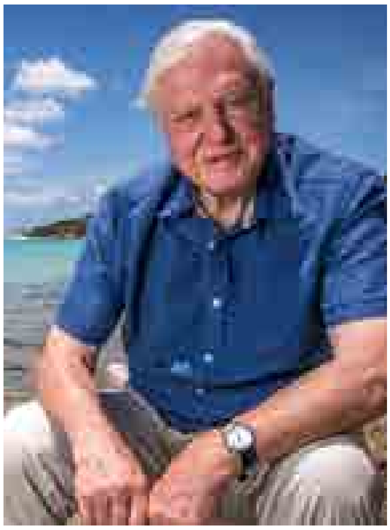
Geographically, the decadal plan concentrates on Australia and New Zealand, including their island and Antarctic territories and their surrounding oceans and territorial waters. Some aspects are also relevant to the broader Australasian region, which also includes the Indo-West Pacific, Papua New Guinea, Indonesia and Timor Leste.

The marine worm *Lanice viridis*, named in 2015 among 91 new species of polychaete worms discovered on Lizard Island in the Great Barrier Reef during a two-week international expedition and taxonomy workshop held there in 2013. Many new marine species like this await discovery in Australia and New Zealand.

CREDIT: © ALEXANDER SEMENOV

Burrunggui, Kakadu World Heritage Area. The sandstone escarpments, wetlands and savanna woodlands of Kakadu are rich in biodiversity, and taxonomically under-explored.
CREDIT: STEVE PARISH

Foreword



A lifetime producing natural history documentaries has taught me many things. Among them, three stand out.

Firstly, the living planet is an utterly astonishing place, filled with marvellous creatures living remarkable lives.

Secondly, people all over the world have an insatiable curiosity about nature.

And thirdly, there is a great need to communicate the wonder, value and diversity of the living world if we are to ensure that we can hand to future generations an environment as rich and marvellous as ours.

I've also come to appreciate the work of the many scientists whose lives are dedicated to understanding nature.

And perhaps none more so than the taxonomists and biosystematists who have discovered, resolved, named and described all the species I showcase in my documentaries.

Taxonomists and biosystematists build the system, the species and their relationships, on which much of biology, conservation, ecology—and nature documentaries—depend. We cannot properly grasp or understand the natural world without this taxonomic system. Every time I show the world a species and its life, I depend on the work of these scientists.

And yet, in countries the world over, at the very time that many species are under greatest threat, funding and other resources allocated to the task of discovering, naming and documenting nature are declining. Our taxonomic capacity is not adequate for the magnitude of the task. This has serious consequences for the future of life on Earth.

This decadal plan provides an important vision, and outlines what taxonomists and biosystematists working in Australia and New Zealand could achieve if properly supported. It focuses on a region of global megadiversity and comes at an important time.

Australia and New Zealand together have some of the most extraordinary organisms anywhere on Earth. However, the world is experiencing mass extinctions, and Australia and New Zealand are not immune.

I commend this decadal plan, and trust that its recommendations will be considered seriously. They have important implications for the future of taxonomy and biosystematics, and in turn for the future of our living planet.

Sir David Attenborough OM CH CVO CBE FAA FRS
Broadcaster and naturalist

15 March 2018

The year is 2028

The year is 2028. A class of high school students are investigating the shoreline of a tidal inlet as part of a biodiversity learning module developed by a local museum and university. The students are documenting recovery of the estuary following streamside revegetation programs in the upper catchment. Some collect water and sediment samples while others sample seaweeds and animals from an inshore reef. All creatures are identified where possible using images, identification guides and other information accessed via an augmented-reality app; those that can't be identified are carefully photographed and returned, the photographs uploaded to the project's Cloud storage.

By the time they get back to school, many of the photographed species have been identified by a deep-learning AI bot. The students genome-sequence their water and sediment samples using plug-in sequencers on their smart phones. Within a few hours, they have compiled a complete listing of all organisms sampled that morning. The good news is that species diversity in the estuary is steadily increasing. One of the eDNA records, however, has been flagged by the national biosecurity agency as a potential match for a serious invasive mussel. The students resolve to head back out next week to try to confirm this and to collect specimens.

The year is 2028. A researcher at a major robotics start-up in a high-technology hub is designing bomb-detecting robots that can crawl through confined spaces. The researcher trawls a database of organisms with unusual morphologies, looking for ones that best match her design requirements. She finds a good target—a cave-dwelling spider described just that year by taxonomists documenting subterranean animals at prospective mine sites.

Contacting the taxonomists, she learns that the species is a member of a newly-described family of spiders, and that several related species have not yet been formally named. After negotiating a collaborative benefit-sharing arrangement for her research, she receives high-resolution CT scans of specimens, and begins to design a robotic version of one of the animals. It works perfectly in trials and goes into production, named after its spider model.

The year is 2028. A woman at an afternoon barbeque in Cairns swats a large, annoying, black-and-white-striped mosquito that's just bitten her on the arm. Recalling photographs in recent media posts on her social feed, she wonders if the mosquito could be an invasive Asian tiger mosquito. Worried that it might be carrying serious diseases, she keeps the dead mosquito and passes it the next day to a local biosecurity officer. DNA tests show that it is indeed an Asian tiger mosquito, and what's more shows that it carries a recently evolved, highly virulent and drug-resistant strain of Zika virus. The woman is quarantined and successfully treated, and the area where the barbeque was held fumigated to kill any further mosquitoes. Further testing in a high-containment quarantine facility shows that the same virus strain can be transmitted by several newly discovered native Australian mosquitoes. Fortunately, extensive surveys of these new species show that the virus has not established in Australia. The Cairns Asian tiger mosquito outbreak is also quickly controlled.

Silver beech (*Lophozonia menziesii*; Māori *tawhai*) forest in Westland, New Zealand. The southern beeches are an ancient group found on fragments of Gondwanaland, and have a rich fossil record.
CREDIT: KERRY FORD

The year is 2028. A new class of antibiotics has just been discovered in a rare family of deep-sea sponges, recently described from specimens collected 30 years previously. The antibiotic is highly effective against all known multidrug-resistant 'superbug' bacteria, but also produces dangerous side-effects in patients. Fortunately, a recently-completed study has determined fine-scale evolutionary relationships among sponges, and this provides a breakthrough—a related compound combines the antibiotic effectiveness with a low side-effects profile. The discovery is timely, as the latest highly drug-resistant tuberculosis strain is beginning to spread rapidly.

The year is 2028. The number of newly discovered and named species in Australia and New Zealand has doubled in the past decade, with major increases in all groups of organisms, particularly marine invertebrates, insects, fungi and bacteria. Australia and New Zealand are the only countries in the world to have achieved such a major increase, and the so-called 'Australasian model' is being rolled out in other countries, particularly those that are biologically megadiverse. Capabilities have been created for a step change to 'hypertaxonomy'—the complete documentation of the region's biodiversity within a generation. Analyses show that improved taxonomic documentation and the rapid delivery of biodiversity information and tools to stakeholders has had direct economic, environmental and social benefits to industry, government, scientific research and the community. Enhanced taxonomy and biosystematics have reduced uncertainty in biosecurity, opened opportunities in food production and industry, and significantly improved conservation efforts and the ability to deliver on international commitments to mitigate the impacts of global change and extinction. A decadal plan for Southern Hemisphere taxonomy and biosystematics 2028–2037 is nearly ready for release.

The year is 2028. A young Māori researcher seconded to a collaborative biosecurity research program establishes a regional knowledge repository with the support of her tribe and community. The initiative is part of a renaissance in Māori cultural knowledge, occurring at local and tribal levels in Aotearoa/New Zealand, that enhances collaboration between science and mana whenua (Māori with historical and territorial rights over the land). The recovery and restoration of traditional knowledge aligned to native biota is an exciting outcome, which supports the development of Māori youth in their understanding and expression of whakapapa (relationships among species) through the science of taxonomy and biosystematics. This knowledge is valued by current and future generations for its contribution to the expression of indigenous identity and potential social and economic value.

The year is 2018.

This decadal plan aims to make these scenarios possible.

Executive summary: A vision for taxonomy and biosystematics 2018–2027

Our planet teems with life. From the billions of bacteria, fungi and other microbes in our soils and seas to the myriad creatures that create and inhabit coral reefs, rainforests, wildernesses and agricultural landscapes, Earth is alive.

A sound understanding of biodiversity is critical, particularly as we seek to achieve both environmental and economic sustainability in the face of rapid environmental change. And yet, our understanding of life on Earth is limited. Best estimates suggest that a majority—around 70%—of Australian and New Zealand species remain undiscovered, un-named and un-documented.

Taxonomy and biosystematics—the disciplines of biology that study, document, name and characterise biodiversity—provide the framework for this much-needed sound understanding of life on our planet.

Taxonomists and biosystematists bring value to multiple sectors of society and the economy, including:

- In ***food production, trade and biosecurity***, by identifying and helping prevent pests and diseases from reaching our shores.
- In ***medicine and public health***, through contributions to drug development and discovery, disease control, and public health risk management.
- In ***ecology and environmental science***, by providing the knowledge that helps environmental managers and governments make balanced decisions, and understand how our environment is changing.
- In ***industry***, through knowledge that inspires new products and services based on millions of years of evolutionary 'research and development'.
- In ***science***, by providing a key underpinning framework for the whole of biology, and exploring some of the biggest scientific questions, such as how life first arose, how it has evolved over time, and why it is so rich and diverse.
- In ***society***, by stimulating and fostering connections between people and their environment, based on knowledge of the diverse species with which we share our planet.

Australian and New Zealand taxonomists and biosystematists have important opportunities and global responsibilities. We have access to, and a responsibility to document, our globally unique and remarkable plants, animals and other organisms, a rich and diverse biota that is essential to understanding the evolution of life on Earth.

This decadal plan presents an agreed vision for the disciplines of taxonomy and biosystematics in Australia and New Zealand in the decade 2018–2027. It seeks to:

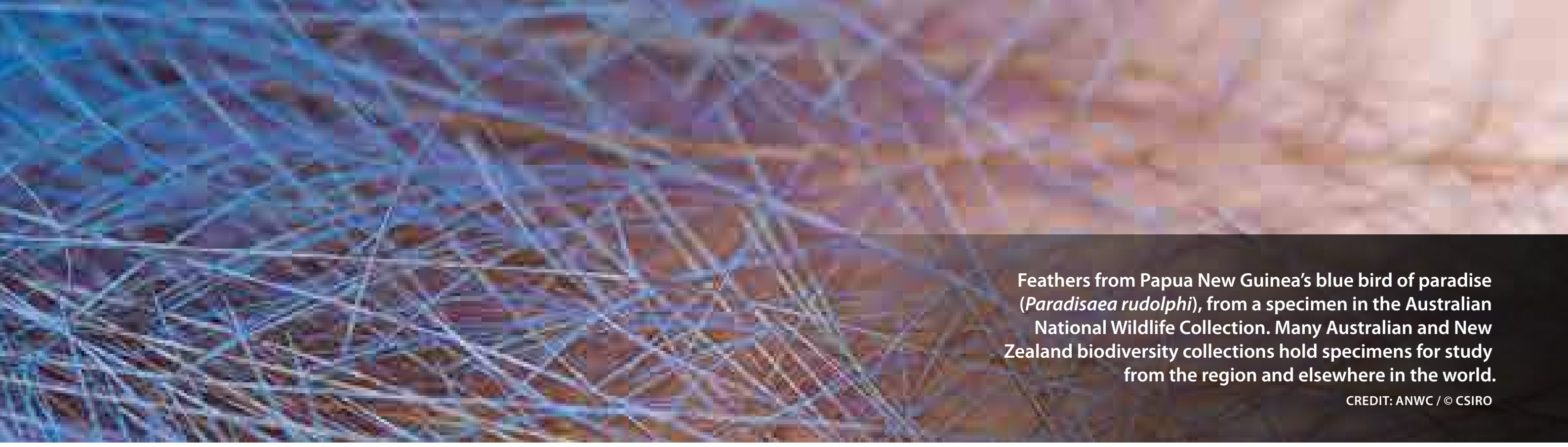
- ***support*** the core activities, workforce and infrastructure of taxonomy and biosystematics
- ***enhance*** opportunities for understanding biodiversity and assisting end users of taxonomic and biosystematic knowledge
- ***expand*** both the business of taxonomy and biosystematics in Australia and New Zealand, and awareness of the importance and roles of the disciplines.

Supporting, enhancing, and expanding taxonomy and biosystematics and their role in science and society is important. We are living through an unprecedented global crisis, caused by rapidly accelerating human impacts on the planet. Many species are becoming extinct before they have been documented, and every extinction is a loss for society, the environment, and our future. The need for a sound understanding of biodiversity has never been greater.

The vision of taxonomists and biosystematists in Australia and New Zealand is to invigorate and boost taxonomy and biosystematics in our countries, to help provide a better response to this urgent need.

Many elements are in place that will allow Australian and New Zealand taxonomists and biosystematists to lead the world. Taxonomy and biosystematics are undergoing a revolution, fuelled by the confluence of new methods and concepts, the ready availability of vast new data streams, and powerful computing. All these are developing exponentially, and driving rapid change in capabilities and opportunities.

This decadal plan seeks to use these new and emerging technologies, to develop key missing infrastructure, and to tie all these elements into a unified and dynamic science that will serve the needs of society, government, industry, and our unique biodiversity.



Feathers from Papua New Guinea's blue bird of paradise (*Paradisaea rudolphi*), from a specimen in the Australian National Wildlife Collection. Many Australian and New Zealand biodiversity collections hold specimens for study from the region and elsewhere in the world.
CREDIT: ANWC / © CSIRO

In the decade 2018–2027, the taxonomy and biosystematics community, with appropriate investment and support from government, industry and society, intends to:

- ***Significantly accelerate species discovery and documentation of Australia's and New Zealand's unique organisms***

  We seek to create a step change in the rate at which we document our biota, and to build capacity and capabilities to drive an acceleration to hypertaxonomy—the comprehensive documentation of Australian and New Zealand species before mid-century. We are the only OECD countries in a megadiverse region; we aim to be the first OECD countries to fully document our biodiversity.

- ***Enhance services for end users of taxonomic and biosystematic knowledge***

  Taxonomists and biosystematists, especially in Australia and New Zealand, have a long history of translating research into accessible forms for end users. New technologies, including in data management, integration, machine learning and mobile platforms, will substantially enhance these knowledge transfers.

- ***Engage with Indigenous communities to ensure that their perspectives, needs and aspirations are incorporated across the activities of this plan***

  Understanding and recognising the deep connections Indigenous peoples in both our countries have with biodiversity and biodiversity knowledge, we will respectfully engage and partner with communities and cultural custodians to create opportunities for mutual exploration of biodiversity.

- ***Integrate and enhance taxonomic and biosystematic infrastructure, particularly our dispersed biodiversity collections, into a distributed science infrastructure that will support the world's best biodiversity science***

  Well-managed biodiversity infrastructure is key to delivering high-quality science, services, and this plan. Australia and New Zealand are currently world leaders in managing and deploying biodiversity knowledge. This plan seeks to ensure that this leadership is not lost.

- ***Ensure that future generations, and the community at large, recognise and celebrate the unique value and immense potential of Australia's and New Zealand's biota***

  Education is key to the future of taxonomy and biosystematics, and ultimately to conservation, sustainable use of biodiversity, and rich cultural relationships with the living world. We seek to inspire our children, our university students, and our communities to appreciate the richness of our biodiversity and the importance of biodiversity knowledge.

- ***Support strategic growth of taxonomic and biosystematic capacity and capabilities in Australia and New Zealand***

  The vision outlined in this plan can be realised only if the taxonomy and biosystematics workforce is strategically enhanced and supported, to ensure that taxonomic expertise is available where and when it is required by our nations.

The taxonomy and biosystematics communities in Australia and New Zealand recognise that this plan is ambitious in scope. Substantial enhancement and change in the taxonomy and biosystematics sector in Australia and New Zealand are necessary and, we believe, achievable. The plan provides high-level goals and actions that will enable its ambitions to be realised.

The plan's success will depend on the commitment of all key stakeholders to drive the necessary changes, on appropriate resourcing from a variety of sources, and on its strategic implementation. A key recommendation is the establishment of appropriate mechanisms in each country to deliver the plan including advocacy, development of underpinning implementation plans, development of resourcing proposals, and coordination of enhanced engagement within the sector and between the sector and its stakeholders and end users.

The taxonomy and biosystematics community in Australia and New Zealand has endorsed this plan, and commits to its implementation to the greatest extent possible, given appropriate investment, resourcing and capacity-building.

Boyd's forest dragon (*Lophosaurus boydii*) is a common species in the Wet Tropics of Queensland. The lichen is a species in the widespread genus *Usnea*.

CREDIT: TAPIO LINDERHAUS

1 Foundations: Taxonomy and biosystematics in science and society

UNDERSTANDING THE RICHNESS OF THE LIVING EARTH, PRESENT AND PAST, IS THE TASK OF THE CLOSELY CONNECTED DISCIPLINES OF TAXONOMY AND BIOSYSTEMATICS.

Biodiversity is crucial for human wellbeing and survival, and taxonomy and biosystematics provide a key framework for understanding biodiversity. Living organisms provide all foods, most medicines, many industrial products, and critical ecosystem services.

Understanding the richness of the living Earth, present and past, is the task of the closely connected disciplines of taxonomy and biosystematics. Taxonomists and biosystematists explore the biosphere much as astronomers explore the universe. They discover, discriminate and name species and other taxa[1], and seek to understand their evolution and relationships.

Taxonomy and biosystematics directly benefit society by underpinning conservation, biosecurity, agriculture, aquaculture and fisheries, bioprospecting, health, and innovative industries. In Australia, taxonomy and biosystematics directly support over two-thirds of agreed national research priorities.

What taxonomists do

Taxonomists discover, discern, describe, name, classify, study, compare and identify the world's living and extinct species and other taxa. Their core task is to document the living world.

Recognising a species is only the first step in its documentation. Newly discovered species also need to be named, described and classified if they are to be recognised, studied and understood by others. Taxonomists use a universal and internationally accepted naming system, governed by a body of agreed rules, to ensure that taxon names are unambiguous and precise. Taxonomic names and classifications are the key framework around which global knowledge and understanding of biodiversity can be organised and accessed.

Taxonomists also provide authoritative syntheses and summaries of current knowledge about the characteristics, genetics, life history, ecological functions, distributions and relationships of taxa, provide tools and services that allow them to be identified and recognised, and help maintain the publicly accessible collections of scientific specimens that provide the anchor points for our biodiversity knowledge.

What biosystematists do

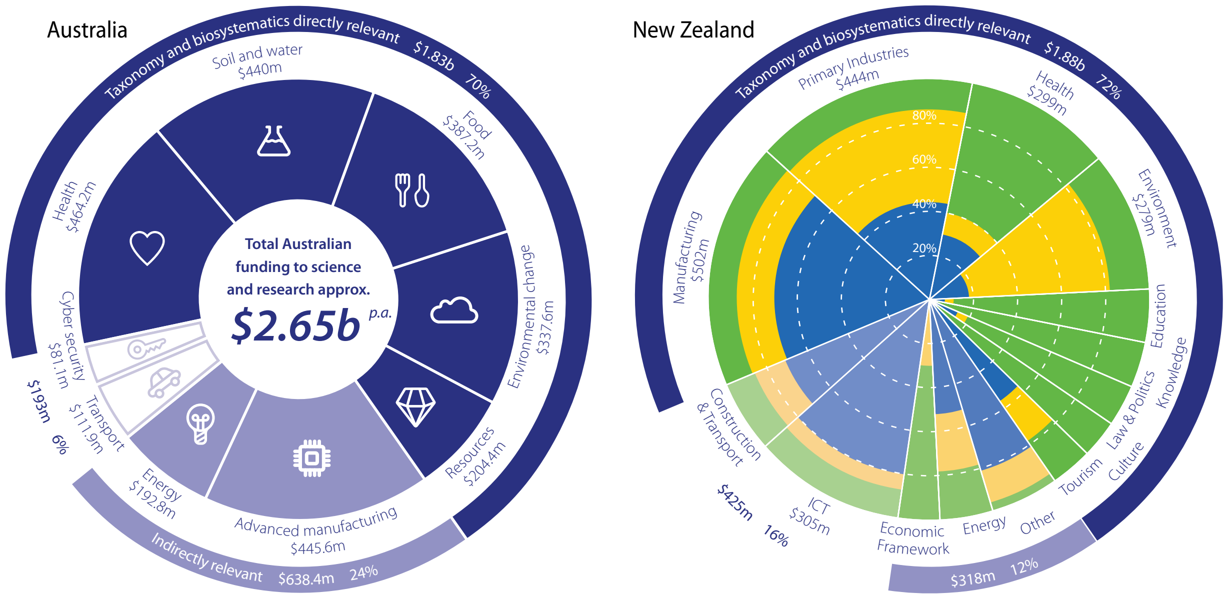
Biosystematists study the big picture. The diversity of living organisms on Earth is the result of billions of years of evolution, and biosystematists study evolution. Biosystematics and taxonomy are closely linked: we need to study evolution to make sense of biodiversity, and we need to document biodiversity to understand evolution.

Biosystematists seek to ensure that the classification of organisms, into genera, families and higher categories, is founded on evolutionary relationships. Well-founded, scientifically rigorous classifications allow predictions about the properties and traits of organisms, and this is an important requirement for many other branches of biology, both pure and applied.

Taxonomy and biosystematics together provide the framework by which we understand the living world.

1 A *taxon* (pl. *taxa*) is any formally classified and named unit of biodiversity. Species, subspecies, genera, families, orders, phyla etc. are all taxa. Taxa are arranged in a hierarchy; species belong to genera, genera to families, families to orders, and so on.

Figure 1: Relevance of taxonomy and biosystematics to Australian[2] and New Zealand[3] research priorities



Relevance of taxonomy and biosystematics to sector
- Directly relevant
- Indirectly relevant

Expenditure sector
- Higher Education
- Government
- Business

A stand of the Critically Endangered Wollemi pine (*Wollemia nobilis*) in a remote sandstone gorge near Sydney.
CREDIT: J. PLAZA / © ROYAL BOTANIC GARDENS SYDNEY AND DOMAIN TRUST

1.1 Conserving our natural heritage

Taxonomists and biosystematists provide critical support for conservation planning, environmental assessment, monitoring and management, ecological research, and other objectives of a sustainable society. They do this by discovering, characterising and naming species and other taxa, enabling and providing identifications, and providing key inventories of species without which conservation planning and actions would be limited.

A poor or incomplete taxonomy of rare species or invasive pests and diseases may exacerbate species declines and extinctions, leading to accelerated and unmanageable environmental change and loss, both biological and economic. Poor or incomplete knowledge of the status and distributions of taxa and of biological richness often leads to poorly targeted and economically wasteful conservation planning.

A comprehensive understanding of Australian and New Zealand biodiversity is necessary if we are to meet international, national and regional targets for conservation and sustainable development. Taxonomy and biosystematics are also necessary to underpin legislated schedules of threatened species and ecological communities, live import lists for approved species, and lists of species or biological materials prohibited (or restricted) for import on biosecurity grounds.

2 Australia's Science and Research Priorities; see http://science.gov.au/scienceGov/ScienceAndResearchPriorities/Pages/default.aspx

3 National Statement of Science Investment 2015–2025; see http://mbie.govt.nz/info-services/science-innovation/pdf-library/NSSI%20Final%20Document%202015.pdf

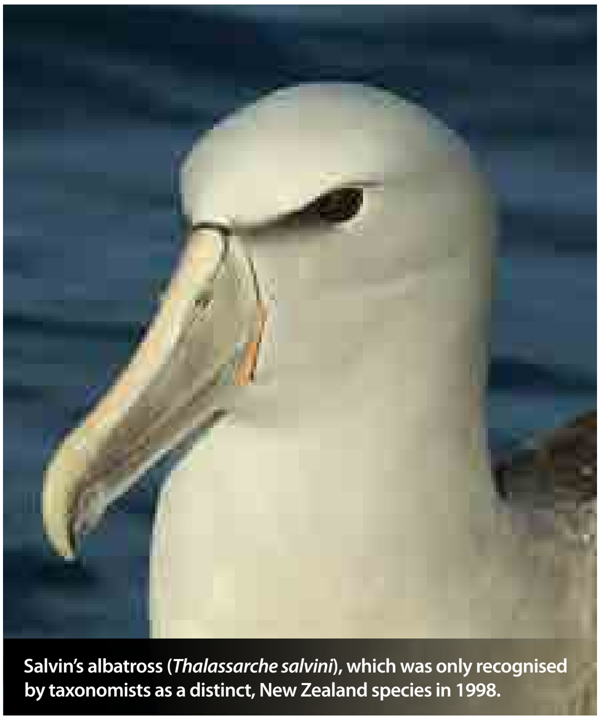
Southern Shortfin Eel, *Anguilla australis*.
Mitchell River National Park, Gippsland, Victoria.

How much can inadequate or uncertain taxonomy cost?

NZ$100 million—when the relatively harmless bacterium *Clostridium sporogenes* was misidentified in 2013 as the potentially fatal *C. botulinum*, resulting in a recall of New Zealand export milk products, with subsequent losses and compensation.

A$35 million—when a shipment of Australian wheat was rejected by Pakistan in 2004 on the basis that it contained the serious wheat disease karnal bunt (caused by the fungus *Tilletia indica*). The shipment in fact had small quantities of a related but harmless minor disease of weedy grasses.

A$5 million—spent on consultancy services and road realignments to conserve the threatened, Tasmanian endemic 'roadside wallaby grass' *Rytidosperma popinense*, later found to be the introduced *R. fulvum*, a common and widespread species in mainland Australia.



Salvin's albatross (*Thalassarche salvini*), which was only recognised by taxonomists as a distinct, New Zealand species in 1998.

Taxonomy and international obligations

Taxonomy and biosystematics underpin our responses, obligations and actions under:

- Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
- The United Nations Sustainable Development Goals
- Convention on Biological Diversity
- The Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization
- World Heritage Convention
- Convention on International Trade in Endangered Species of Wild Fauna and Flora
- Convention on Migratory Species
- The Antarctic Treaty
- Convention on the Conservation of Antarctic Marine Living Resources
- Convention for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean
- The Ramsar Convention on Wetlands
- The United Nations Framework Convention in Climate Change
- The Mataatua Declaration
- Te Tiriti o Waitangi

1.2 Protecting our borders

Taxonomists working in biosecurity document and identify the pests and pathogens that threaten biodiversity, agriculture and human health, thereby contributing to the management of risks posed by these organisms. If our taxonomy of potentially invasive organisms is not robust, accurate and well founded, the chances of a new pest or disease breaching quarantine is greatly increased, with potentially devastating consequences. Taxonomic uncertainty may also increase costs for importers and exporters by delaying the accurate identification of intercepted organisms.

In 2017, taxonomists and biosecurity diagnostics staff in Australia identified 32 744 specimens in 21 519 biosecurity incidents, seeking to determine if shipments of goods and agricultural products contain exotic pests, diseases or other classified organisms that cannot be allowed through our borders. If undetected, many of these organisms have the potential to cause multibillion dollar losses to the economy and trade, and immense damage to the environment.

Biosecurity also depends on a good understanding of native biodiversity. Shipments often contain organisms that may or may not be native to Australia or New Zealand; if the taxonomy of native species is unresolved, a definitive assessment of an organism's status may be impossible. Robust and authoritative diagnostic tools for identifying invasive pests cannot be developed effectively if the taxonomy of native relatives has not been adequately established.

Biosecurity decisions need to be evidence-based, particularly when they impose additional costs on importers. Stronger, more defensible decisions depend on a good understanding of the taxonomy of both native and non-native species.

The northern Pacific sea star *Asterias amurensis*, a serious pest of aquaculture, in the Derwent estuary.
CREDIT: CSIRO CC BY 3.0

Taxonomy and biosecurity: the contrasting incursions of *Mytilopsis sallei* in Darwin Harbour and *Asterias amurensis* in the Derwent River

In late March 1999, divers surveying the Port of Darwin for potential marine pests discovered dense colonies of an unidentified shellfish in Cullen Bay Marina. Within two days, specimens were identified as the invasive black-striped false mussel (*Mytilopsis sallei*) by a specialist taxonomist at the Museum and Art Gallery of the Northern Territory.

Mytilopsis sallei is a world-wide pest in harbours and other inshore marine environments, where it fouls pylons, jetties, boat hulls, mooring ropes and mangroves. It poses a serious threat to aquaculture, including pearl farms and commercial and recreational fisheries throughout tropical and warm-temperate parts of the world. Economic losses from two closely related species in the Great Lakes of North America currently exceed US$500 million per year.

Although the species had almost certainly been in Darwin Harbour for less than six months, it was found to be spreading rapidly on the hulls of ships and small boats.

Within a week of its detection, the Northern Territory Government declared a State of Natural Disaster, closed and quarantined all Port of Darwin marinas, and instigated a successful eradication campaign, one of very few examples of successful eradication of a marine pest anywhere in the world. The last known living individual of *Mytilopsis sallei* in the Port of Darwin, and hence in Australia, was killed a few weeks later. A potential marine economic and environmental disaster was averted.

Rapid identification by readily available taxonomic experts was instrumental in the successful response to the black-striped false mussel in the Port of Darwin.

Conversely, lack of available expertise was instrumental in the failure to eradicate an equally serious invader, the northern Pacific sea star *Asterias amurensis* in southern Australia. When specimens of this pest were first collected in the Derwent River in the late 1980s they were mistakenly identified as a native species due to a lack of available expertise in sea star taxonomy. A six-year delay before the specimens were correctly identified means that the northern Pacific sea star is now ineradicable. It has since spread to Victoria, and is now likely to expand to sheltered waters throughout southern Australia. A voracious predator, it has destroyed scallop fisheries in Tasmania and Victoria, and will continue to cause irreparable and increasingly costly damage to aquaculture and marine environments.

Khapra beetle and Australia's grain export industry

Australian export earnings often depend on the country's status as being free of highly trade-sensitive pests and pathogens. Fast and effective eradication of incursions of these species is essential. An important aspect of this is maintaining a good understanding of native species that may be similar to, or close relatives of, the trade-sensitive exotics.

The globally serious grain pest *Trogoderma granarium* (Khapra beetle), which does not occur in Australia, is difficult to distinguish from many closely related native *Trogoderma* species, which are not agricultural pests. Rapid diagnostics are needed when *Trogoderma* beetles are detected in import or export commodities.

Australia is a global hotspot for this genus, with more than 100 native species of *Trogoderma*, many of which have not yet been identified or described. Further taxonomic work on this complex genus is needed to develop tools that can adequately distinguish the invasive pest from the benign native species. These tools will reduce the likelihood of future costly mistakes caused by misdiagnoses.

Adults and larvae of the Khapra beetle *Trogoderma granarium*, a globally serious pest of stored grain products.

A *Varroa destructor* bee mite on its host.
CREDIT: CHRIS POOLEY / USDA

Bee mites: the importance of taxonomy for biosecurity

Bee mites of the genus *Varroa* are major pests in Western honeybees, causing millions of dollars of damage to apiary industries and pollination services worldwide. They are a major biosecurity threat to the Australian bee-keeping industry.

When bee mites were first identified as causing significant losses in overseas apiaries, their taxonomy was poorly understood. Work by taxonomists at CSIRO's Australian National Insect Collection led to the discovery that two different species of mites were infecting bees.

One species (*V. jacobsoni*) was found to be restricted to one honeybee strain in southern mainland Asia and Indonesia, where its impacts were relatively minor. The other, a new species named *V. destructor*, was found in honeybees throughout the world, causing millions of dollars of damage each year. All other species of *Varroa* tested were found to be harmless to Western honeybees.

Having clarified the taxonomy of the species, taxonomists were able to provide morphological and genetic means to identify the mites, allowing Australian quarantine officials to improve biosecurity and incursion management strategies.

Between 2000 (when the taxonomic work was published) and 2007, economic benefit from this taxonomic work was estimated at over A$100 million, with a benefit:cost ratio of 17:1.[4]

The gains, however, may be short-lived. Although the taxonomy of *V. jacobsoni* and *V. destructor* is now resolved, the taxonomy of bee mites as a whole is still poorly understood. Many native species, any of which could in future impact honeybees, remain unnamed and poorly understood. Much more taxonomic work is needed before we can successfully manage the risks from these pests.

4 ACIAR Impact Assessment Series Report No. 46, July 2007

1.3 Feeding the world

Taxonomists and biosystematists seek to understand and characterise the organisms that impact our agricultural and aquacultural systems, both positively and negatively. Understanding the taxonomy of pests and pathogens; discovering new and more effective biological control agents; documenting wild relatives of crop plants and animals to discover genes that may improve yields or resist disease; and exploring the taxonomy of soil and aquatic microbes, all help to increase and maintain agricultural and aquacultural yields in Australia and New Zealand and around the world.

A teaspoon of fertile soil may contain up to one billion bacteria, up to a hundred metres of fungal filaments, thousands of protozoa and hundreds of tiny invertebrates, comprising up to several thousand distinct species. Most of these have never been named, and we have little idea what most of them do.

1.4 Discovering the drugs of the future

The world's species represent an enormous pharmacological resource, in the form of a staggering diversity of potentially useful biochemical compounds that remain undiscovered in living organisms. Carefully targeted bioprospecting requires a sound understanding of species and their evolutionary relationships, an understanding provided by taxonomy and biosystematics.

> Fifty per cent of all pharmaceutical compounds registered for use in the USA are derived from, or were originally discovered in, living organisms.[5]

Only a small fraction of Australia's and New Zealand's living organisms have ever been tested for pharmacologically active compounds. Because our diverse biota has evolved in isolation for tens of millions of years, it is likely to offer a wealth of new and potentially valuable biochemical products.

Taxonomy and biosystematics of rice and its Australian native relatives

Rice (*Oryza sativa*) is an essential source of carbohydrate for billons of people. Approximately 500 million tonnes of rice is milled per annum, with a market value of A$15 billion.

Taxonomic and biosystematic studies indicate that northern Australia harbours previously unknown native rice species, some closely related to cultivated rice. This discovery, made by Australian taxonomic researchers in Queensland, provides significant opportunities for industry and agriculture.

Australian wild rices can be readily hybridised with crop rice, providing opportunities for breeding cultivars with improved properties for new markets, including enhanced drought tolerance to reduce the very high water needs in paddy rice cultivation. They are also key resources for genes to breed varieties that are resistant to the many pests and diseases that threaten rice production throughout the world.

Australian native rices are also likely to have their own pests and diseases, some of which may in future threaten cultivated rice. Documenting these is important if we are to reduce the chance that they will become serious new risks.

A nudibranch *Tambja verconis*. Nudibranchs are highly toxic, and are being investigated for drugs and other compounds.
CREDIT: JULIAN FINN / MUSEUMS VICTORIA CC BY-NC 4.0

A recently discovered species of native Australian rice, *Oryza meridionalis*.
CREDIT: © QAAFI / UNIVERSITY OF QUEENSLAND

5 Chivian E. & Bernstein A., eds 2008. *Sustaining Life: How Human Health Depends on Biodiversity* (Oxford University Press, New York)

The Bob Marley sponge, *Pipestela candelabra*, the type species of a new genus, and a source of potentially valuable pharmaceuticals from the Great Barrier Reef and Coral Sea.
CREDIT: QUEENSLAND MUSEUM

Drug discovery and the taxonomy of marine sponges

Sponges are one of the oldest groups of multicellular animals. They have very high genetic and taxonomic diversity, and complex symbiotic relationships with other organisms including bacteria. Because sponges don't move, and live in an environment rich in predators, parasites and competitors, they and their symbionts have developed an astounding arsenal of protective chemical compounds to ward off attacks and compete with faster-growing species.

Such compounds provide important opportunities for discovering new and powerful pharmaceuticals, including anti-cancer drugs and antibiotics. Of 8 500 new potential pharmaceuticals discovered from marine organisms over the past decade, nearly 2 500 are from sponges, the largest single taxonomic group providing potential new drugs. Drug discovery screening of sponges has led to a range of drugs approved for use in humans, including the HIV antiviral compound Avarol from the sponge *Dysidea avara*, and the cancer drugs Cytarabine, Yondelis®, Eribulin and Adcetris®. Other potential drugs in clinical trials include hemiasterlins and diisocyanoadociane from recently discovered species in the new Australian genus *Pipestela*. These compounds are active against serious human parasites including drug-resistant strains of malaria.

Careful taxonomic and biosystematic studies on sponges is key to the research and development leading to these new drugs. Great progress has been made since 1980 by taxonomists at the Queensland Museum and New Zealand's National Institute of Water and Atmospheric Research (NIWA) in documenting the sponges of Australasia. More than 1 600 sponge species have been named in Australia, and nearly 1 300 in New Zealand including its Antarctic territories. However, at least 3 000 more species are known but have not yet been named or documented[6, 7]. Many more await discovery in the vast, under-explored marine economic zones of Australia and New Zealand, which together comprise the world's largest claimed national seabed jurisdictions.

Bioprospecting, and the drug discovery and development that follows, needs a solid taxonomic and evolutionary underpinning. Valuable compounds will be missed if the taxonomic foundation is not firm and comprehensive.

6 http://spongemaps.org/
7 https://niwa.co.nz/our-services/online-services/nic

1.5 Improving human health

As well as playing a key role in the discovery of new drugs and other pharmaceuticals, taxonomists and biosystematists study the organisms that cause human diseases and affect our health, both positively and negatively. Many disease-causing viruses and bacteria, both emerging and well established, have not yet been named or studied. And medical researchers have uncovered profound links between microbial biodiversity in and on our bodies—the human microbiome—and aspects of health, ranging from mood to weight, and the risks of a wide range of diseases and medical conditions.

Doctors of the future may become ecologists and farmers of the human microbiome, carefully manipulating our internal biodiversity to cure disease and keep us healthy. Taxonomists study the microbiome using sophisticated genomic methods to understand its diversity and to identify key bacteria and other organisms, many of which are currently unnamed.

1.6 Enabling industrial innovation

Biodiversity provides important and innovative solutions for industry. New industrial processes based on living organisms are being invented every year, accelerated in recent years by gene technologies that can engineer the cellular biochemistry of bacteria, algae and other microorganisms to produce medicines, fuels, plastics and other organic chemicals.

Living organisms are also consummate engineers and innovators, and have been experimenting, through natural selection, for billions of years. The discovery of every new species has potential to unlock important solutions to present or future problems.

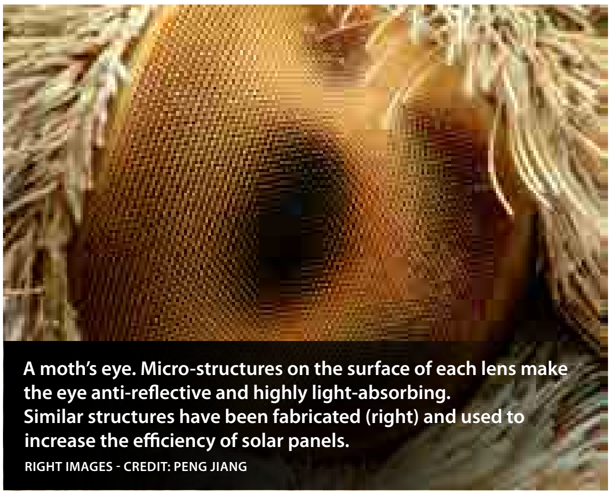
> *"You can look at nature as being like a catalogue of products, all of which have benefited from a 3.8-billion-year research and development period. And given that level of investment, it makes sense to use it."*
>
> — *Michael Pawlyn,* Biomimicry Institute[8]

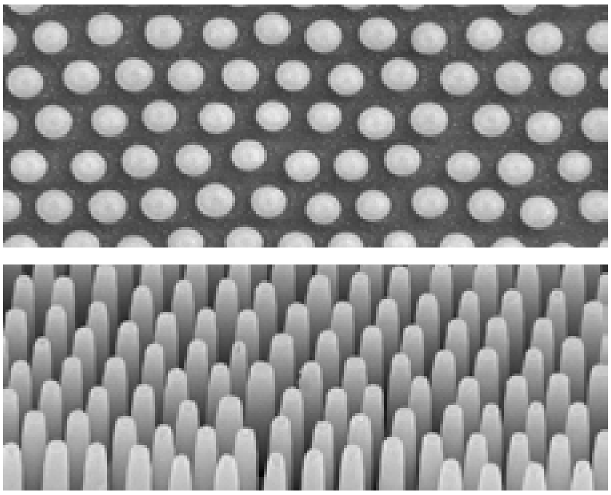
Biomimicry

Biomimicry is an approach to innovation that seeks inspiration and concrete solutions to human challenges and needs in organisms and natural systems. Examples of successful innovations inspired by biomimicry include:

- vaccines that can be dehydrated and do not require refrigeration (inspired by so-called 'resurrection' animals and plants that can dehydrate completely but remain alive)
- super-efficient wind turbine blades with knobbed rather than smooth surfaces (inspired by the fins of humpback whales)
- water-repelling, anti-reflective glass coatings that increase the yield of solar panels (inspired by microscopic patterns on the surfaces of moth eyes)
- super-strong and resilient materials based on spider and insect silks
- bacteria-killing surfaces and materials based on the nanostructure of dragonfly wings.

Biodiversity in our region holds globally significant potential in biomimetics, as it has a very long and unique evolutionary history. Taxonomists and biosystematists can make significant contributions in this emerging field.





A moth's eye. Micro-structures on the surface of each lens make the eye anti-reflective and highly light-absorbing. Similar structures have been fabricated (right) and used to increase the efficiency of solar panels.
RIGHT IMAGES - CREDIT: PENG JIANG

8 https://biomimicry.org

1.7 Enhancing public awareness

Almost everyone connects in some way with the natural world. Many people connect by knowing the names of birds, wildflowers, trees, fungi, mammals and other species, or through nature-based tourism. Many others are engaged in citizen science projects that monitor, map or explore biodiversity. Social media platforms and apps that connect people with biodiversity are proliferating. All of these directly rely on the understanding of species provided by taxonomists, an understanding that facilitates, promotes and supports a love of life, a connection with biodiversity, and an important sense of the need for stewardship of the Earth.

12 264 – the number of downloads, *in the first two days*, of FrogID, an app from the Australian Museum for identifying, discovering and helping conserve Australia's frogs.

1.8 Biodiversity and Indigenous knowledge

Australia's and New Zealand's Indigenous peoples have rich and comprehensive biodiversity knowledge systems and nomenclatures, based on a deep understanding of the characteristics, behaviours, habits and habitats of many species. It is important to ensure that today's young people and future generations can share this knowledge, and that it remains embedded in a dynamic culture and inheritance.

Indigenous communities and taxonomists share an understanding of the importance of biodiversity knowledge. Building on and enhancing these shared values, and sharing knowledge, provides powerful opportunities for engagements that can lead to benefits to all partners.

Shining a Māori light on moths

Ahi Pepe MothNet[9] seeks to unlock the natural curiosity of primary school children and help them see the significance of New Zealand's native moths. Ahi means fire and Pepe means moth, which literally translated means the "moth fire", a reference to a whakataukī (proverb) about the light of a fire attracting moths.

Students learn how to trap, identify and pin moths, and to compare moth species that occur in different ecological communities and in native forests compared with disturbed and revegetated areas. A core component is a series of moth guides written in Te Reo Māori that focus on five whakataukī about moths and their life cycles.

Nearly 2 000 species of native moths and butterflies have been documented and named in New Zealand, 90% found nowhere else in the world. Several hundred more are estimated to remain undiscovered.

Ahi Pepe MothNet weaves science, culture and language together, all based around the whakapapa of the moth—the connection of moths to people, the world, and New Zealand's ecosystems.

Collecting reptiles on a BushBlitz expedition at Kiwirrkurra, Western Australia.
CREDIT: ROB DAVIS

Ahi Pepe Mothnet participants studying moths in a New Zealand forest.
CREDIT: AARON WILTON / MANAAKI WHENUA LANDCARE RESEARCH CC BY 4.0

9 https://landcareresearch.co.nz/information-for/citizen-science/mothnet

1.9 Enabling sustainability

Sustainability of biodiversity and the prosperity of human societies are inextricably linked. By characterising biodiversity, taxonomists and biosystematists provide the framework and tools by which others can study change and resilience of the Earth system in the face of past, present and future stresses. This has never been more important than at present, when living organisms from the most remote polar and desert regions to the deepest oceans are under threat from human-induced environmental change including global warming, pollution and extractive industries, and are key to ameliorating and managing those threats. From carbon capture and storage in soils and the oceans, to detoxification of pollutants and regulation of geochemical cycles, sustainability without a deep knowledge of biodiversity is impossible.

Trying to manage the Earth sustainably without an adequate taxonomy is like trying to manage the world's largest, most complex corporation without an adequate inventory of stock and with no real idea of what most of the products look like or do.

1.10 The sciences of life

Taxonomy and biosystematics are fundamental to all life sciences, from the microcosm of genetics, DNA, and the smallest components of cells, to the macrocosm of the global environment and its ecology. Without an understanding of the structure of life provided by taxonomy and biosystematics, sciences across this spectrum would be severely compromised.

By exploring the depth and breadth of the living world, and seeking to understand its origins, diversification and structure, taxonomists and biosystematists address some of the most profound questions in science: What is life? How is it structured? How has it evolved? And what does the future hold for life on Earth?

> *'The ongoing neglect of biodiversity research […] diminishes the capacity to meet one of the greatest challenges to the biological sciences, rising just over the horizon: the origin, evolution and equilibration of ecosystems. The problems presented by ecosystem analyses are equivalent in complexity to those presented by the human brain. They can be solved by nothing less than a Linnaean renaissance, in which each one of the millions of Earth's species still surviving is discovered and its role in the biosphere increasingly well documented.'*
>
> *— E.O. Wilson*[10]

A geometrid moth, *Pingasa chlora*. Moths are very diverse and taxonomically poorly known. Many species in Australian and New Zealand biodiversity collections have not yet been named.
CREDIT: TAPIO LINDERHAUS

10 E.O. Wilson (2017) Biodiversity research requires more boots on the ground. *Nature Ecology & Evolution* 1: 1590–1591.

Taxonomists and biosystematists support many other life and other sciences, including:

- **ecology**—by ensuring that species and other taxa (the subjects of most ecological studies) are scientifically robust, well characterised, and can be accurately identified
- **genetics**—by providing the evolutionary and taxonomic framework that allows an understanding of genetic diversity and evolution
- **geology**—by characterising and documenting the fossils that form the basis of much of stratigraphy and, hence, are key to mining and oil and gas exploration
- **Earth science**—by enabling documentation of biogeochemical cycles that help stabilise and drive the Earth system
- **oceanography**—by discovering and documenting the organisms, many of them microscopic and poorly studied, that underpin and drive ocean productivity
- **climate science**—by enabling past, current and future climate change to be tracked, through an understanding of their effects on species and ecological communities.
- **agricultural science**—by characterising pests, diseases, beneficial organisms and the wild relatives of crop plants
- **medicine**—by enabling deeper, more accurate knowledge of the microbiome and of human pathogens
- **ethnobiology**—by supporting and enabling Indigenous contributions and engagement with biodiversity
- **environmental science**—by discriminating species and supporting an understanding of life histories and management of natural resources and species stocks
- **conservation science**—by providing the authoritative species names that underpin conservation planning and legislation.

All these sciences need a robust and scientifically valid understanding of the species and other taxa they study, and need to ensure that the taxa they work with are correctly identified and understood. Their studies may be severely compromised and not reproducible if this is not the case.

BASE – Characterising Australia's soil microbiome

Soil microbes, including bacteria, archaea and fungi, are amongst the most important organisms on Earth. Soil microbes are global ecosystem engineers, driving carbon, water and nutrient cycles, supporting the nutrition of plants and vegetation, and acting as, or against, pathogens, pests and diseases.

Despite their central importance and direct impacts on agricultural and natural productivity, the taxonomic and genetic diversity and evolutionary relationships of the organisms that make up soil microbe communities are very poorly understood.

Over the past five years the Biomes of Australian Soil Environments (BASE) project has used next-generation genetic analysis of soil samples from more than 900 sites sampled across the continent to measure and model Australia's soil microbiome. Billions of DNA sequences have been assembled and databased, revealing a previously undocumented richness in genetic, functional and taxonomic diversity in this crucial community.

Modelling the diversity against environmental variables has also begun to reveal how and why the Australian soil microbiome varies across the landscape and across different taxonomic groups, how land use affects the soil microbiome, and how soils respond to agricultural and ecological remediation.

The diversity of soil microbes is a key issue in ensuring agricultural and environmental sustainability. Documenting and characterising these ecosystem engineers is a key task for understanding some of the most fundamental ecological processes on Earth.

Collecting soil samples at Uluru for the BASE project. Even sandy desert soils contain many undiscovered species of bacteria and fungi, which the BASE project is characterising.
CREDIT: ANDREW YOUNG

A blue-ringed octopus *Hapalochlaena maculosa*.
Four species of these highly venomous, coastal octopuses are known. However, their taxonomy is unresolved, and up to six currently un-named species are being investigated taxonomically.

2 Snapshot: Australian and New Zealand taxonomy and biosystematics in the year 2018

THE TAXONOMY AND BIOSYSTEMATICS COMMUNITIES IN OUR COUNTRIES HAVE ACHIEVED MUCH. IN THE NEXT DECADE WE CAN ACHIEVE MUCH MORE.

Australia and New Zealand comprise one of the world's most biologically diverse and evolutionarily remarkable regions. Our nations are relatively wealthy and scientifically advanced, with a high capacity for research and development. We have a solid and, in many cases, world-leading base of accumulated knowledge and infrastructure.

Taxonomy and biosystematics are in the midst of a profound technological revolution, triggered by advances in technologies as diverse as genomics, three-dimensional imaging, big data computation and machine learning. These provide opportunities that were unimaginable a decade ago.

A high level of cooperation and connectedness within the Australian and New Zealand taxonomic and biosystematic community places us in an excellent position to harness the benefits of these emerging technologies.

For these reasons, we are in a strong position to gain maximum return from additional investment. The taxonomy and biosystematics communities in our countries have achieved much. In the next decade we can achieve much more.

This section provides a snapshot of:

- what we know (and don't yet know) about Australia's and New Zealand's biodiversity
- our research infrastructure, its capabilities and current limitations
- our workforce of taxonomists, biosystematists and support staff
- the resourcing of taxonomy and biosystematics in Australia and New Zealand.

South Island edelweiss (*Leucogenes grandiceps*), an alpine scree slope endemic in southern New Zealand.
CREDIT: KERRY FORD

An immature rainforest katydid, *Phricta* sp.
CREDIT: TAPIO LINDERHAUS

2.1 Our living biodiversity

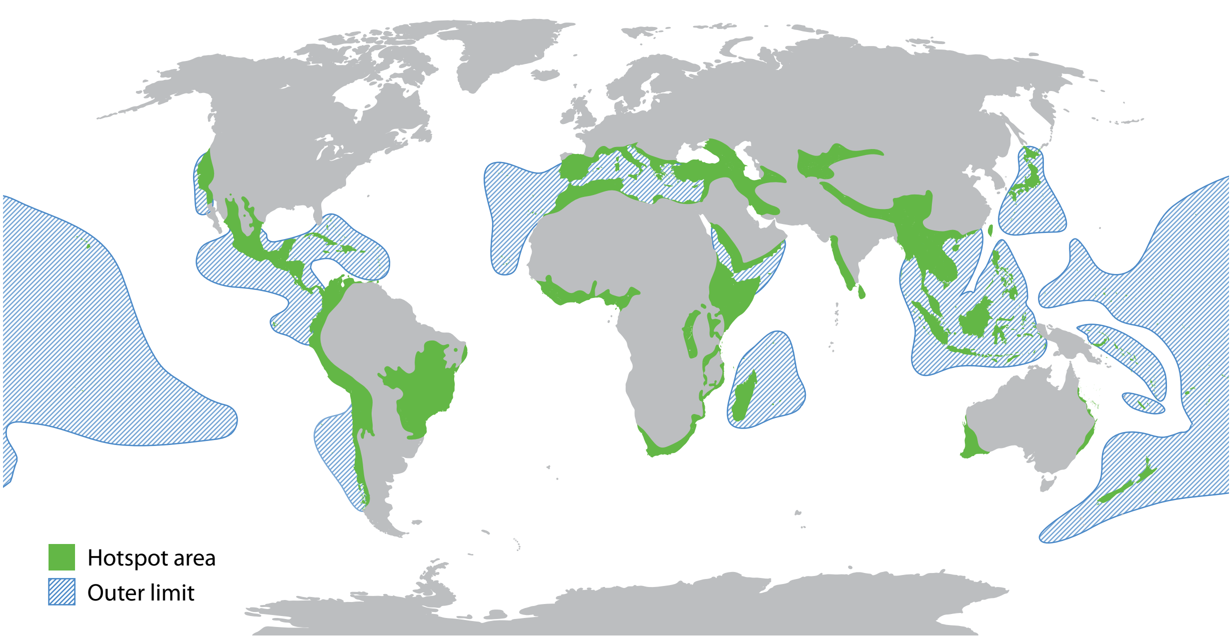
Australia and New Zealand, together with New Guinea and the islands of the Indo-West Pacific, comprise one of the most biologically remarkable parts of the world.

New Zealand and parts of Australia are recognised as global biodiversity hotspots: these areas account for less than 3 per cent of the world's land and ocean surface and contain more than 40 per cent of its endemic species. Australia is also one of 17 countries classed as biologically megadiverse. Together, the megadiverse countries account for less than 10 per cent of the Earth's land surface, but support more than 70 per cent of its terrestrial biodiversity.

2.1.1 Our biodiversity is unique

Our region is also home to an unusually high number of species that are critical to an understanding of the evolution of life on Earth. Many of the world's most evolutionarily significant lineages of plants, seaweeds, songbirds, mammals, reptiles, frogs, fishes, ants, termites and moths are in the Australasian region. No other part of the world holds such a rich concentration of such important lineages.

Figure 2: Global biodiversity hotspots



The world's 35 biodiversity hotspots: representing just 2.3 per cent of Earth's land surface, these contain about 50 per cent of the world's endemic terrestrial plant species and 42 per cent of all terrestrial vertebrates. A serious concern is that these hotspots have lost more than 85 per cent of their original habitat, and are significantly threatened by extinctions.[11]

11 Mittermeier RA, Turner WR, Larsen FW, Brooks TM, Gascon C (2011) Global biodiversity conservation: the critical role of hotspots. In: Zachos FE, Habel JC (eds) *Biodiversity hotspots: distribution and protection of conservation priority areas.* Springer, Heidelberg

Australasia, an evolutionarily remarkable region

Kangaroos and kiwis, as well as being iconic Australians and New Zealanders, illustrate one aspect of the global importance of Australasian biodiversity: we are home to many lineages that are key to an understanding of the evolution of life on Earth. Marsupials, along with the Australian and New Guinean monotremes (platypuses and echidnas), represent the two earliest known living mammal lineages, and are most diverse here. Kiwis, emus and cassowaries are members of one of the earliest-diverging living lineages of all birds. Similarly, the earliest diverging lineages of songbirds, the world's largest group of birds, are the New Zealand wrens and the Australian lyrebird and scrub birds.

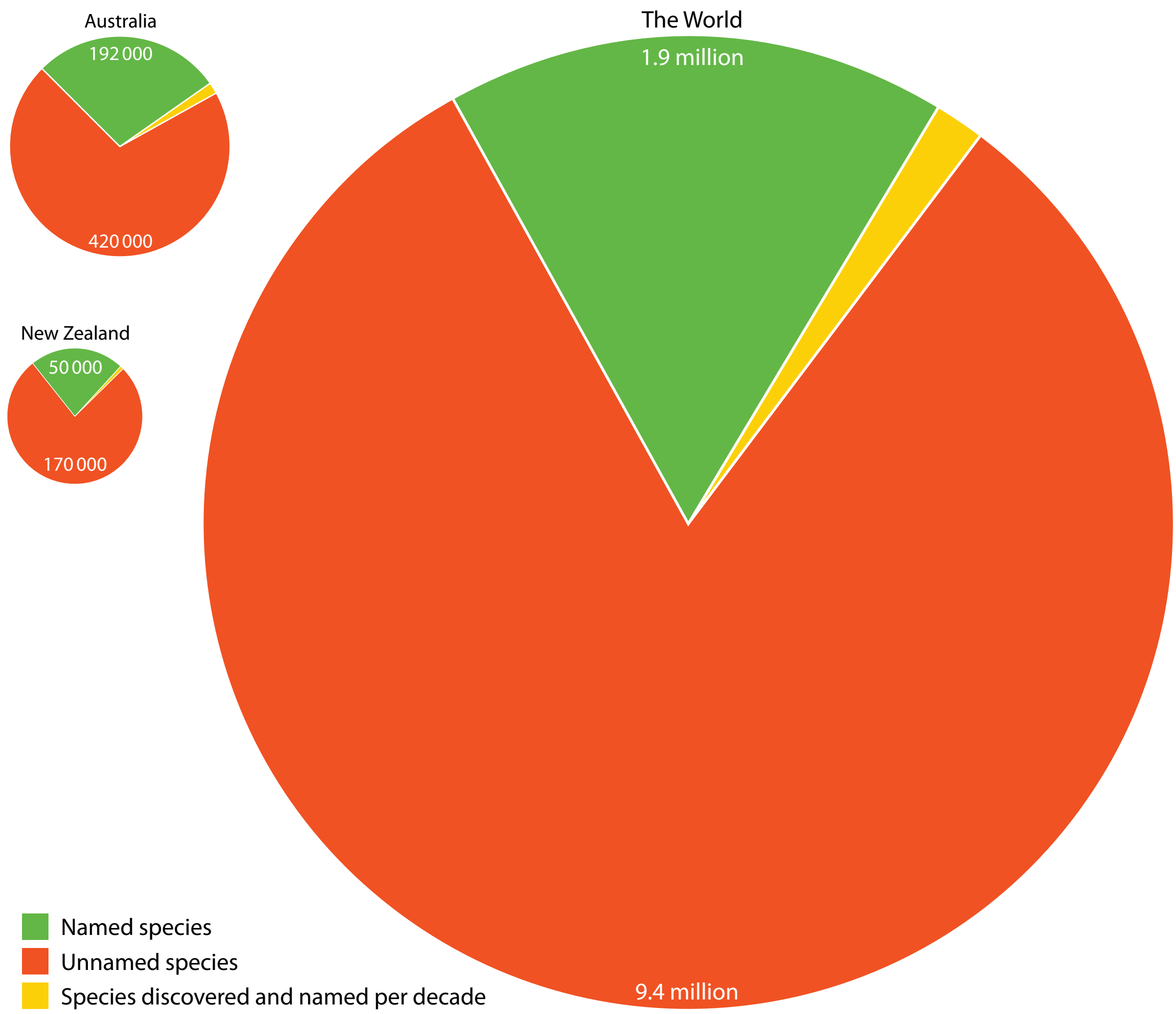
Other examples include:

- New Zealand's remarkable tuatara, the closest living relative to all the world's snakes and lizards
- the world's earliest-diverging surviving lineage of frogs, New Zealand's leiopelmatids
- *Amborella*, a rare plant endemic to New Caledonia (part of the ancient geological continent of Zealandia), which represents the most ancient surviving flowering plant lineage
- the Wollemi pine *Wollemia nobilis*, previously known only from 200 million-year-old fossils until found living in a small canyon near the Blue Mountains in New South Wales
- the rare ant genus *Nothomyrmecia*, also known as the dinosaur ant, a relict lineage among ants only known from southern Australia
- Tasmania's enigmatic anaspidid crustaceans, which date back over 200 million years
- the salamanderfish *Lepidogalaxias salamandroides*, endemic to heathland pools in southwestern Australia and the sole surviving species in an ancient lineage of fishes that diverged from the ancestor of all other fishes over 150 million years ago.

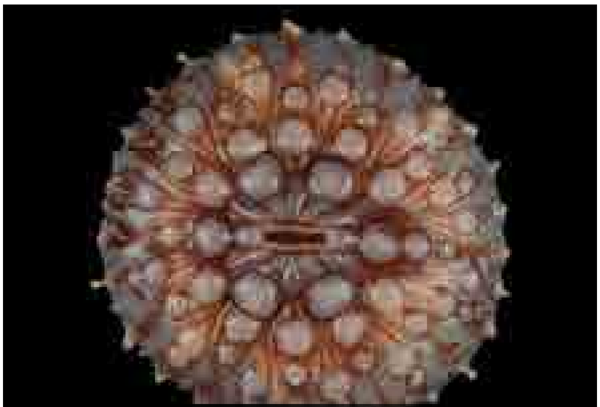
Any attempt to understand the history of life on Earth starts with an understanding of the taxonomic and evolutionary relationships of these Australasian lineages.

New Zealand's remarkable tuatara (*Sphenodon punctatus*). While lizard-like, true lizards are more closely related to snakes than they are to the tuatara. The tuatara is the sole surviving member of a once-diverse lineage.

Figure 3: Named and un-named species in Australia, New Zealand and the world



The estimated number of living named and un-named species in Australia[12], New Zealand[13] and the world[14]. The yellow slices represent the average number of new species discovered and named per decade.



***Corallimorphus niwa*, a recently described unusual animal related to stony corals and sea anemones. First collected in 2007 on New Zealand's Chatham Rise, the species name commemorates the New Zealand National Institute of Water and Atmospheric Research (NIWA), one of New Zealand's significant biodiversity collections.**

CREDIT: OWEN ANDERSON / NIWA

2.1.2 Our biodiversity is rich, and largely undocumented

We currently estimate that approximately 830 000 species of plants, animals, fungi, algae, microbes and other organisms occur in Australia and New Zealand, of an estimated 11 million species in the world. Nearly 30 per cent of Australian and New Zealand species are estimated to have been discovered and named, compared with less than 20 per cent for the world as a whole.

Some taxonomic groups are relatively well documented, while others are very poorly known. In general, more charismatic and readily visible groups such as mammals, birds, flowering plants and butterflies are relatively well documented, and less charismatic or visible groups such as many insects and other invertebrates, fungi and bacteria are mostly very poorly known.

12 Cassis, Laffan & Ebach (2016), Biodiversity and Bioregionalisation Perspectives on the Historical Biogeography of Australia, in Ebach, M (2016), ed., *Handbook of Australasian Biogeography* (Taylor & Francis: Melbourne)

13 Gordon (2009–2012) New Zealand Inventory of Biodiversity (Canterbury University Press: Christchurch)

14 http://www.esf.edu/species

Trays of specimens at the Australian National Insect Collection, CSIRO. Canberra. The collection comprises more than 12 million specimens from throughout Australia and the world.
CREDIT: AUSTRALIAN NATIONAL INSECT COLLECTION / © CSIRO

Cataloguing the diversity of life: Inventories of biodiversity

Taxonomists in Australia and New Zealand have produced authoritative inventories of biodiversity, both known and (estimated) unknown.

The three-volume *Inventory of New Zealand biodiversity* involved a team of 238 specialists from 19 countries. The living and fossil, terrestrial, freshwater, and marine biodiversity of New Zealand was catalogued and reviewed, amounting to 56 200 named living species and 14 700 fossil species. No other nation has such a comprehensive inventory. The Inventory formed the basis of the New Zealand Organism Register (NZOR), an online database of all known, named New Zealand species.

In Australia, the Australian Biological Resources Study (ABRS) manages the National Species List[15] and Australian Faunal Directory[16], which together catalogue over 400 000 names of more than 170 000 taxa of plants, fungi and animals in Australia. These are maintained by the taxonomic community throughout Australia, in association with state and territory biodiversity censuses.

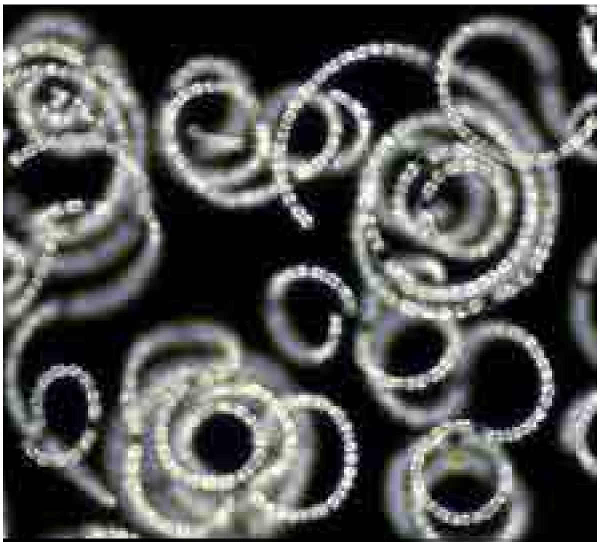
An important inventory of fossil organisms in New Zealand[17] is maintained by the Geosciences Society of New Zealand and GNS Science. The Paleobiology Database[18] has a global span that includes New Zealand and Australia.

The foundational importance of these checklists cannot be overstated. Many activities, including government and industry planning and legislative instruments, rely on authoritative, continuously updated lists of names and taxa.

15 https://biodiversity.org.au/nsl/services
16 https://biodiversity.org.au/afd/home
17 https://fred.org.nz
18 https://paleobiodb.org

How many species are there really?

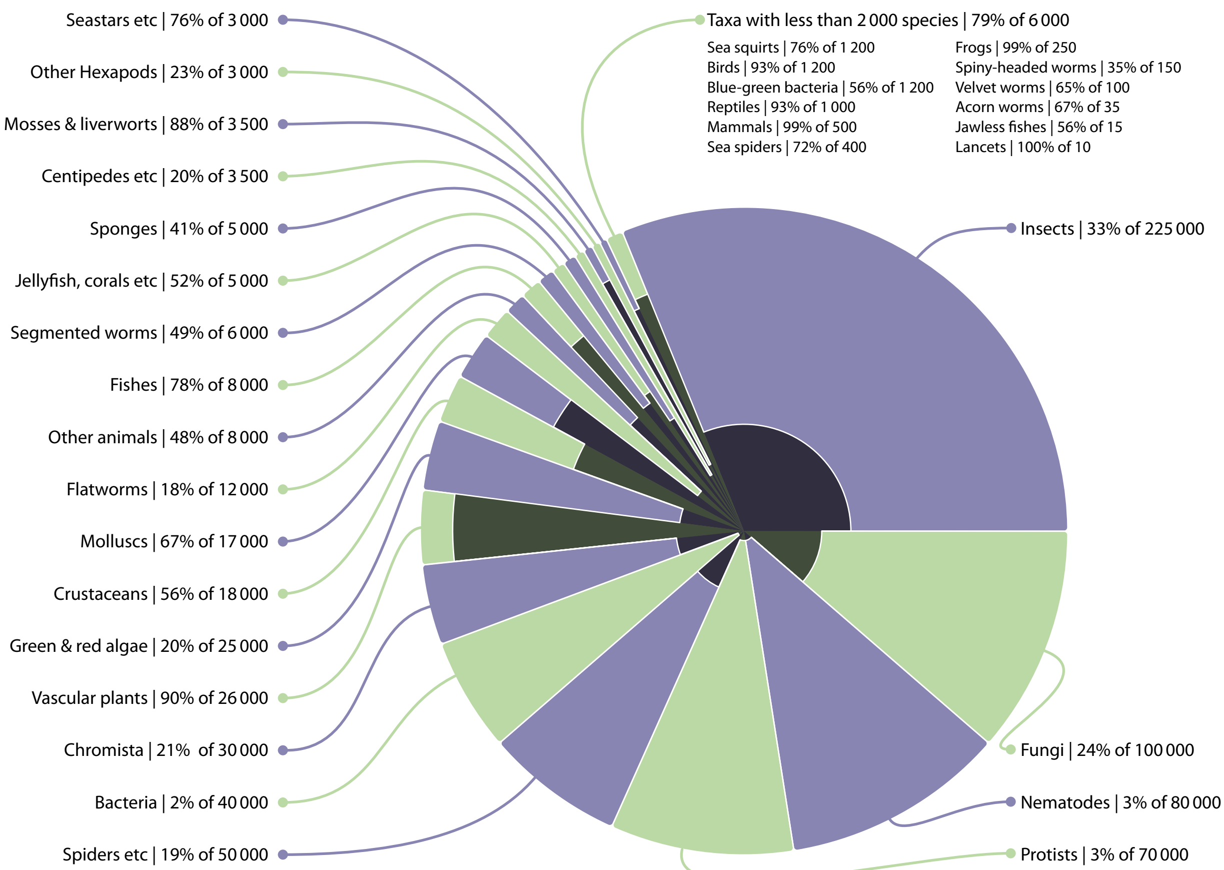
For the purposes of this document, we use a recent estimate that there are likely to be 11 million species on Earth. Estimates such as these are complex; because a large proportion of species have not yet been discovered, and most of these are in the least-understood groups, there are large uncertainties. Although estimating the total number of species is a scientifically important exercise, the task of taxonomy and biosystematics is to document and classify life on Earth as comprehensively as possible, to benefit our understanding of, and ability to utilise and conserve, our biodiversity.



***Anabaena circinalis*, a cyanobacterium. These ancient micro-organisms literally created the conditions for life on earth to thrive when they oxygenated the Earth's atmosphere.**

CREDIT: JOHN HUISMAN

Figure 4: Biodiversity in Australia and New Zealand across different organismal groups



Biodiversity in Australia and New Zealand across different organismal groups. Numbers refer to the sum of estimated species and percentage of these that have been described in Australia[19] and New Zealand[20]. Dark sectors in the centre represent named species (drawn in proportion to radius). Insects and fungi are the two largest groups in the region, followed by nematodes, protists and bacteria. Very few species in these groups have been named; all are hyperdiverse. Note that estimates for total species for these groups are highly uncertain.

19 Chapman (2009) Numbers of Living Species in Australia and the World, 2nd edition (http://environment.gov.au/system/files/pages/2ee3f4a1-f130-465b-9c7a-79373680a067/files/nlsaw-2nd-complete.pdf)

20 Gordon (2009–2012) New Zealand Inventory of Biodiversity (Canterbury University Press: Christchurch)

Whether a group is taxonomically well or poorly documented, however, does not correlate with how important it is, either ecologically, environmentally or for human wellbeing. Microscopic fungi and bacteria, nematodes, and many insect groups, for example, are amongst the most poorly documented of all organisms, yet they recycle nutrients in soils, control pests, cause and prevent disease, and hold enormous potential for industry, agriculture and medicine; such organisms have been described by biologist E.O.Wilson as "the little things that run the world". These groups are also very rich in species, and comprise the majority of Australasian and global biodiversity.

An important reason for the disparity in biodiversity knowledge of different taxonomic groups is that research tools have been inadequate in the past. With recent advancements in taxonomic research technologies, quantum leaps in generating new biodiversity knowledge for these groups can now be made.

Poor documentation caused by low visibility of some taxonomic groups is particularly serious for marine biodiversity. Most of the planet is ocean, yet most of our known species, and most new species discovered each year, are terrestrial. Many iconic and globally important marine areas, such as the Great Barrier Reef and the Southern Ocean around Australia's and New Zealand's territories in Antarctica and the subantarctic islands, remain very poorly documented.

An Asian tiger mosquito *Aedes albopictus*. Asian tiger mosquitoes are major vectors of serious diseases in many parts of the world. They have not yet become established in New Zealand or mainland Australia, and represent a serious biosecurity risk.

Mosquitoes—a critically important (and taxonomically neglected) group

Mosquitoes are well-known and important vectors of diseases in animals and humans, transmitting malaria, dengue fever, Murray Valley encephalitis and other disease-causing pathogens to humans, livestock and wildlife. Globally, mosquitoes cause more human deaths than any other animal.

Around 220 named species of mosquitoes are currently known from Australia. At least 200 more Australian species are believed to exist, but these have never been taxonomically studied, named or documented; for this reason, their disease risk has never been evaluated.

The last formally named Australian mosquito was published in 2001; shortly thereafter, the last Australian mosquito taxonomist took up a position in the United States, and has not been replaced.

Climate change is causing, and will continue to cause, major changes in the prevalence and distribution of known disease-causing mosquitoes and the diseases that they carry. The undocumented species of Australian mosquitoes, and the known and unknown pathogens they may carry, represent a serious risk.

However, the poor state of taxonomic knowledge of Australian mosquitoes means that these risks are unquantifiable. Responses to future disease outbreaks will be significantly hampered by these knowledge gaps, all of which begin with a significant gap in taxonomic knowledge.

Collecting insects and other invertebrates at Olkola, Queensland, during a BushBlitz expedition.
CREDIT: GARY CRANITCH / © QUEENSLAND MUSEUM

2.1.3 The growth of biodiversity knowledge

Knowledge of Australian and New Zealand biodiversity has grown significantly over time. In Australia, the growth of biodiversity knowledge can be divided into five phases. Before the beginning of WWI, both the annual rate and cumulative growth of taxonomic knowledge (measured by the numbers of new species described annually, and the accumulation of known species, respectively) increased steadily. During the period of the two World Wars and the Great Depression, the annual rate of discovery of new species declined dramatically as investment in science and taxonomy declined. With post-war reinvestment after 1950, the rate increased again.

Australian taxonomy and biosystematics then gained a significant boost with the establishment of the Australian Biological Resources Study (ABRS) in 1973 and its dedicated investment scheme and *Flora of Australia* and *Fauna of Australia* programs, along with substantial investments in collections and taxonomy from State governments and CSIRO. A step change in the rate of addition of new species was achieved at this time. From the early 1990s, however, ABRS funding has declined in real terms and the annual rate of naming new species has reached a plateau and begun to decline.

In New Zealand, a decline related to the world wars and Great Depression is evident, ending in 1950, followed by some restoration of capacity with post-war reinvestment. New Zealand has no equivalent of the ABRS, and funding for taxonomic research halved between 1975 and 1995[21]. As a result, the annual rate of discovery and documentation of new species has declined since the early 1970s and is now half the rate achieved before WWII.

Globally, Australia maintains a high rate of species discovery, particularly in well-known groups such as plants and reptiles. In the decade 2004–15, Australia has consistently ranked as one of the top three countries for the discovery and naming of new plant species, along with Brazil and China, despite having substantially fewer botanists. While similar statistics are not available for taxonomic groups other than plants, they are likely to show a similar trend.

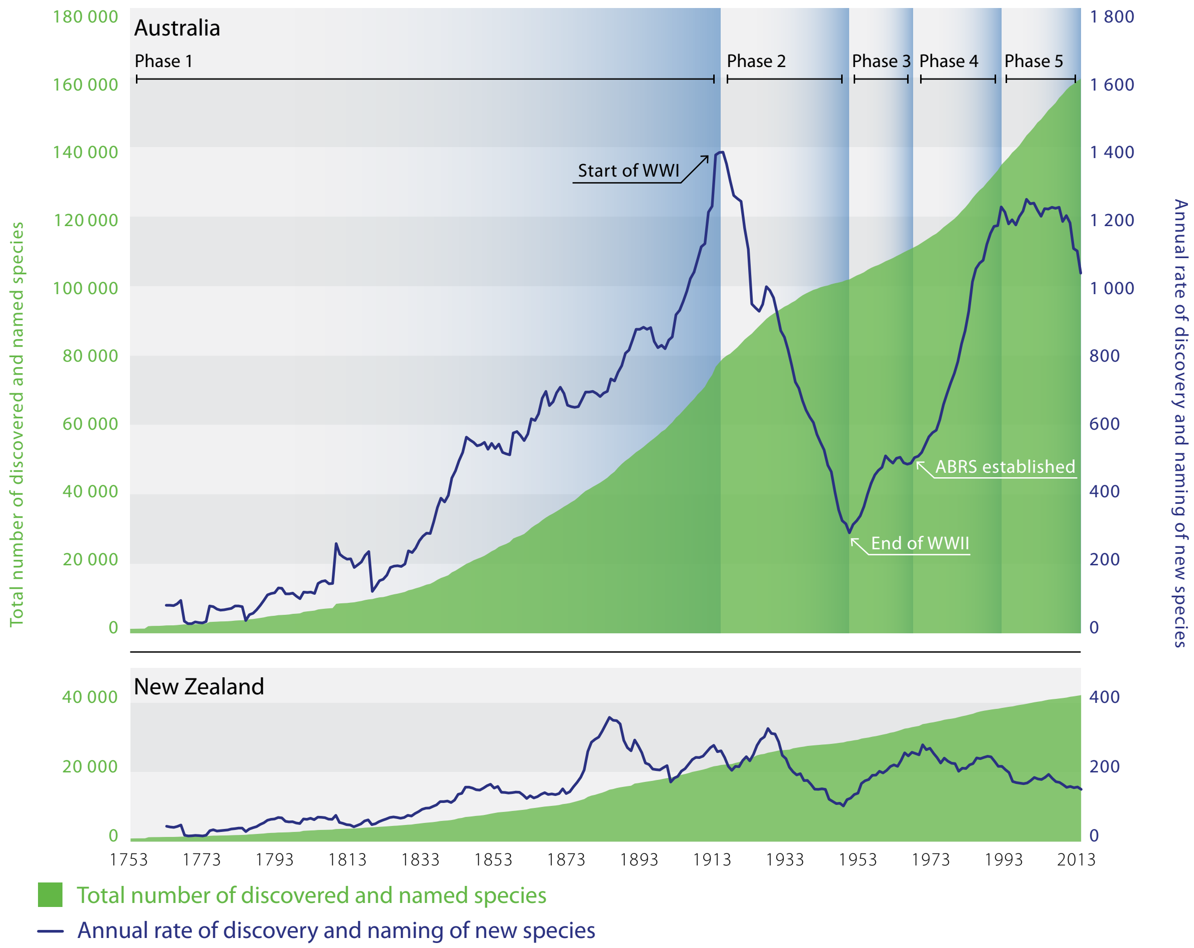
However, although Australian and New Zealand taxonomists and biosystematists are productive, the very rich biodiversity of our region and the large estimated number of undiscovered species means that a comprehensive inventory of Australian and New Zealand species will take centuries at the current rate of discovery and documentation. We are world-class in our capacities; with sufficient new investment, we can be exceptional.

25 000 – the estimated number of new Australian species of plants, animals, fungi, algae and other organisms discovered and named in the decade 2008–2017.[22]

21 Ministry of Research, Science and Technology review (1995). *Biosystematics: Issues and Options for New Zealand*

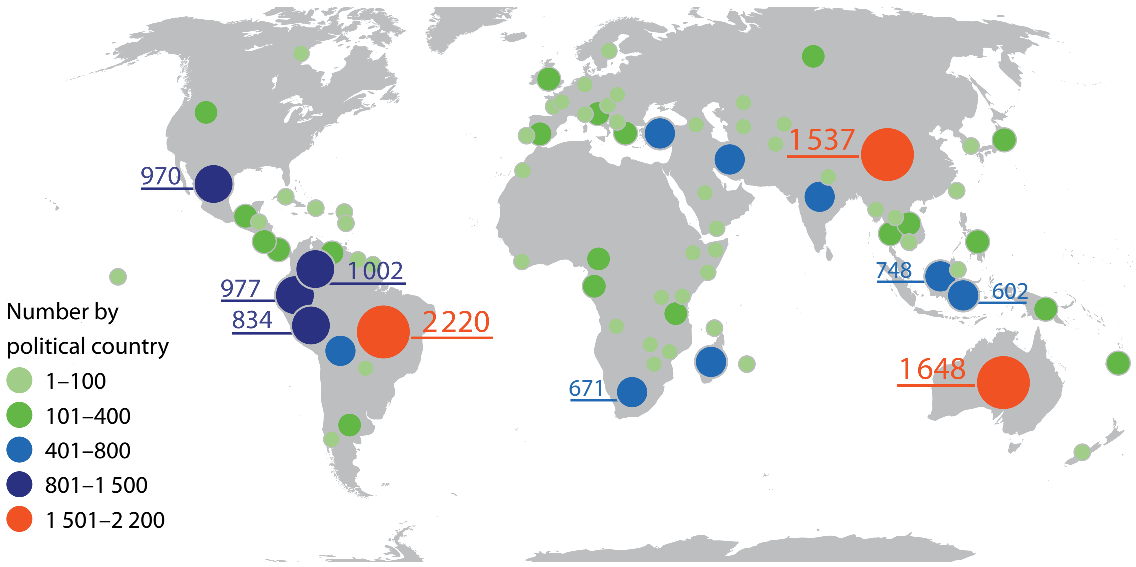
22 Cassis, Laffan & Ebach (2016), Biodiversity and Bioregionalisation Perspectives in the Historical Biogeography of Australia, in Ebach, M (2016), ed., *Handbook of Australasian Biogeography* (Taylor & Francis: Melbourne)

Figure 5: The discovery of new species in Australia and New Zealand, from 1750 to the present



Accumulation (green) and annual rate of discovery and naming of new species (purple) in Australia and New Zealand 1753–2014. Data for Australia from the National Species Lists and Australian Faunal Directory; data for New Zealand from the New Zealand Organism Register.

Figure 6: Numbers of plant species discovered and named in the world, during the decade 2006–2015



Numbers of new plant species discovered, documented and named by country, for the decade 2006–2015.[23]

23 *State of the World Plants 2016*. Royal Botanic Gardens Kew (https://stateoftheworldsplants.com/2016/report/sotwp_2016.pdf)

2.2 Fossil biodiversity

Biodiversity extends through deep time, and the study of fossil organisms and their environments sheds much light on the evolution of life and of the Earth. Australia and New Zealand have a unique and globally important fossil record. The oldest known animal fossils, for example, from the Ediacaran period more than 500 million years ago, were first documented and are best preserved in the Flinders Range in South Australia.

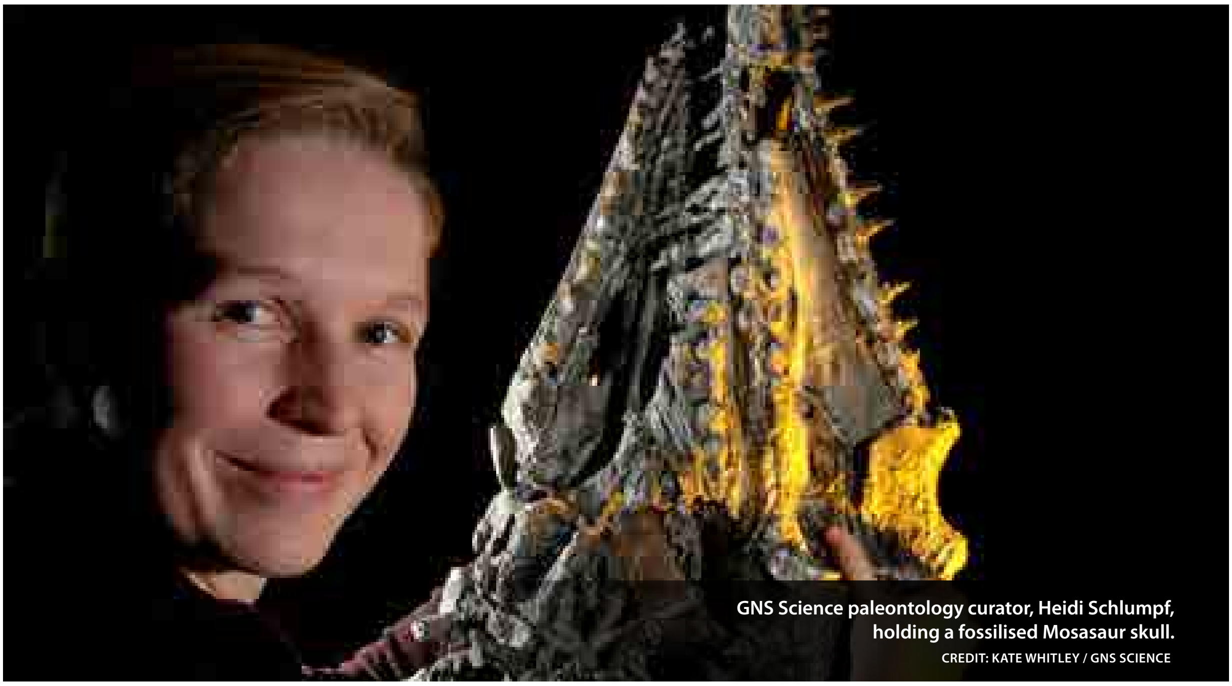
Our fossil record is critical for understanding the impacts of past and future environmental change. Australia and New Zealand have changed immensely during their journeys through time and space since the breakup of the ancient supercontinent of Gondwana. Australia has evolved from a wet, warm continent largely covered in rainforest and intersected by vast rivers larger than today's Amazon, to the largely arid continent we see today. New Zealand has had a more complex and dynamic history, being at some stages substantially larger and substantially smaller than today. Both land masses have spent many millions of years isolated from all others. All these changes had profound impacts on our biodiversity, on land and in the sea. The fossil record documents and helps explain these changes, which in turn helps explain the nature of today's biodiversity.

While some pieces of the puzzle of the past are well understood, many others remain to be explored and explained. Palaeontologists—taxonomists and biosystematists who study the past—have an important role in understanding the evolution of life on Earth. Increasingly, they also have a key role in explaining the likely future. Predicted near-future global climates are more similar to climates from tens of millions of years ago than they are to climates experienced any time during human history; fossils from the past provide key insights into the likely future.

Tracking and calibrating the history of Earth

Fossils of extinct colonial plankton provide crucial clues for dating sedimentary rocks. These fossils – graptolites – have an exceptional evolutionary history in Australasia. Indeed, graptolites have standardised part of the global geological time scale for Ordovician time, 410–485 million years ago. The sequence and abundance of graptolites makes them sensitive environmental indicators, and important tools to help find the geological resources needed by society.

More recent fossils can also help us understand the evolutionary history of our region, and the environmental and climate change that has shaped our flora and fauna. Forty million years ago, southern Australia was rich and diverse in conifers (pines and their relatives); today, many fewer species survive here. Detailed study of fossils shows that conifer species with the highest water requirements became extinct first, while more drought-adapted species survive to the present day. The extinction and changes in distribution of conifers can be used to track the drying of southern Australia in the last 20 million years; this has implications for understanding potential extinctions under current (and future) climate change.



GNS Science paleontology curator, Heidi Schlumpf, holding a fossilised Mosasaur skull.
CREDIT: KATE WHITLEY / GNS SCIENCE

2.3 Biodiversity infrastructure

Taxonomy and biosystematics are underpinned by a substantial infrastructure—collections of scientific voucher[24] specimens and tissue samples, digital collections of specimen records, DNA samples and sequences, and information systems that integrate these records—and by the expert knowledge and capability of staff who manage and curate them. Together, these provide the anchor points upon which knowledge of biodiversity is built, refined and tested, and provide a permanent resource for serving the needs of end users and answering important questions about life on Earth, some of which haven't yet been asked or imagined.

Biodiversity collections comprise preserved voucher specimens of organisms collected at a known place and time, stored permanently under archival conditions, and made available for a wide range of scientific and other studies. Reproducible research in many areas of biology depends on a means to accurately identify organisms being studied, to compare them with large samples of other specimens, and to validate and future-proof observations by linking them to vouchers. Biodiversity collections play a critical role in all these areas.

There are more than 120 public[25] biodiversity collections in Australia and 29 in New Zealand[26], ranging from large museums and herbaria housing many millions of specimens each, to smaller, special-purpose collections such as pathology, germplasm, wood and culture collections. Together, these hold more than 82 million specimens (over 70 million in Australia, over 12 million in New Zealand), with a nominal replacement value of A$8 billion[27]. Built up over centuries, the aggregate collection of voucher specimens in our herbaria and museums is a priceless heritage and a cutting-edge research infrastructure.

Collections are spread across a wide range of jurisdictions. In Australia, each State and Territory manages a museum and herbarium in its capital; some of these are focused primarily on their respective jurisdiction, whereas others are national in scope. Five national collections are managed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Very few collections are located in the tropical north of Australia, a region undergoing rapid development, with its concomitant need for good knowledge of biodiversity to support sustainable development.

In New Zealand, a network of 29 taxonomic collections housed in Crown Research Institutes, museums, tertiary education institutions, and the Cawthron Institute represent the bulk of New Zealand's critical biological collections' infrastructure.

The importance of curation

Biodiversity collections and their databases are not static archives, important only from a historical perspective. They are actively growing and curated scientific resources, continually updated, improved and enhanced as knowledge of biodiversity grows. They are unusual in this respect—the more they are used, the more valuable they become and the 'sharper' they are as scientific tools for understanding the natural world.

Curation (of specimens, data and information) is a key concern of taxonomy and biosystematics. Good curation by well-trained and experienced staff 'future-proofs' our knowledge by ensuring that it is tied to verifiable voucher specimens in the collections.

A pressed herbarium specimen of *Nymphaea violacea*.
CREDIT: CENTRE FOR AUSTRALIAN NATIONAL BIODIVERSITY RESEARCH / AUSTRALIAN NATIONAL HERBARIUM

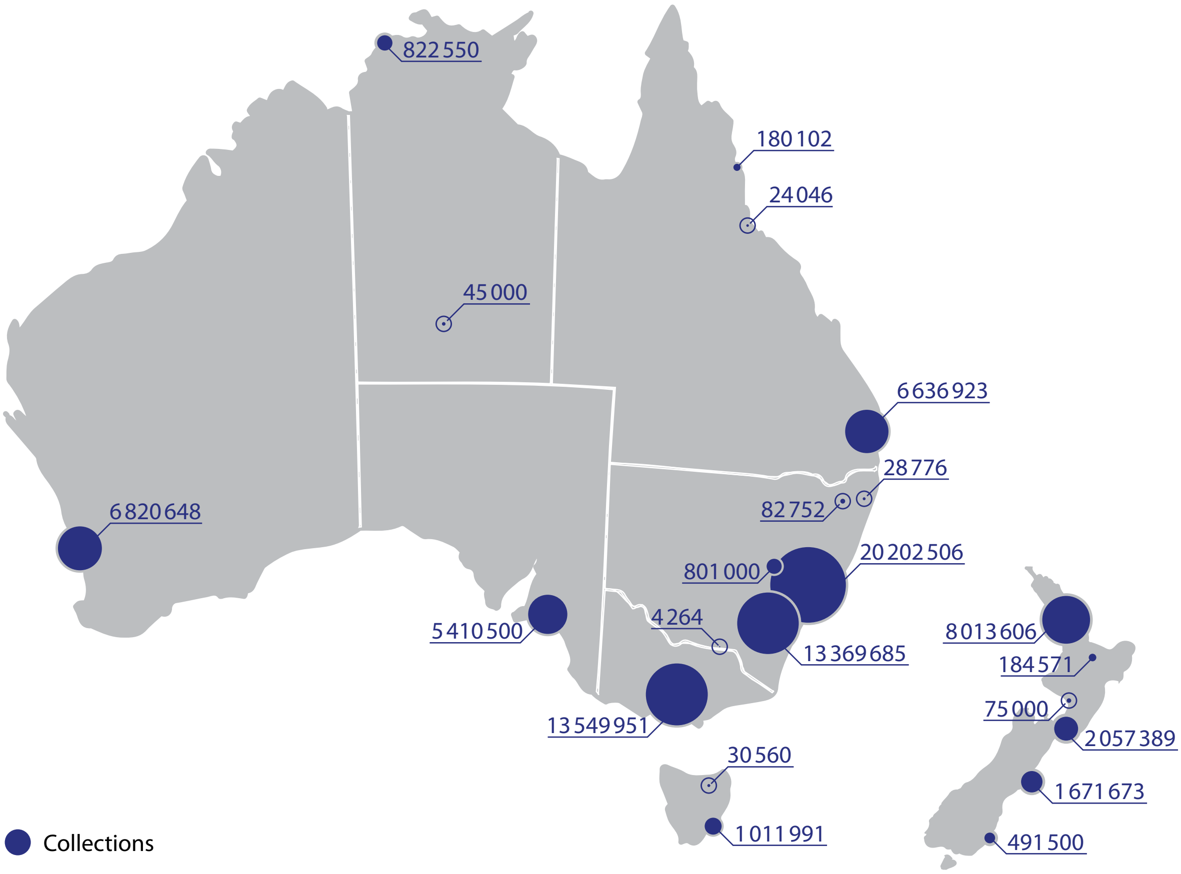
24 Voucher specimens are scientific specimens of organisms. They may be pressed plant specimens, pinned or alcohol-preserved insects and other invertebrates, prepared skins and skeletons of mammals and birds, preserved fish or other animals, cultures of bacteria, fungi or algae, or fossils. Wherever possible, multiple specimens of each species are stored in collections. These document the distribution, abundance, habitat and variation in each species, and are the basis upon which taxonomists discover and delimit new species.

25 Australia and New Zealand have very few privately funded biodiversity collections; with the exception of New Zealand's Cawthron Institute, these are not considered in this plan.

26 Documented at https://collections.ala.org.au and in the report National Taxonomic Collections in New Zealand (https://royalsociety.org.nz/assets/Uploads/Report-National-Taxonomic-Collections-in-New-Zealand-2015.pdf)

27 The estimated cost to re-collect and replace the specimens if destroyed. Note that the scientific value of these specimens, many of which are irreplaceable, is incalculable.

Figure 7: Biodiversity collections in Australia and New Zealand



Locations of larger biodiversity collections in Australia and New Zealand. The area of solid circles represents the total size of the collection (numbers of specimens) in biodiversity institutions at each location. Smaller collections are circled for convenience. Collections with fewer than 1 000 specimens are not mapped.

Biodiversity collections in New Zealand

New Zealand's biodiversity collections were the subject of a detailed report[28] by the Royal Society Te Apārangi in 2015. After reviewing the value and importance of national biodiversity collections and their associated taxonomic research for primary production, biosecurity, conservation, environmental monitoring, human and animal health, natural science, national and international legislative obligations, and for society and mana whenua, the report documented a decades-long erosion of investment and support, and risks to the future sustainability of the collections and of their contributions to New Zealand.

It demonstrated that investment in New Zealand's network of 29 biodiversity collections is fragmented, that collections' infrastructure (physical specimens, taxonomic research, tools and information systems, and associated activities) is largely invisible to beneficiaries, and that there is poor strategic alignment between short-term and long-term priorities relevant to collections and the biodiversity knowledge they contain.

The report concluded that biodiversity collections should be recognised as national heritage assets and essential components of the New Zealand science system, that a whole-of-systems approach is needed to connect providers, custodians, practitioners, stakeholders, and end-users of biodiversity knowledge, and that a single point of responsibility within government should be established to coordinate a coherent approach to policy and investment in the biological collections infrastructure.

28 National Taxonomic Collections in New Zealand, https://royalsociety.org.nz/assets/Uploads/Report-National-Taxonomic-Collections-in-New-Zealand-2015.pdf

One of the specimen stores at the Western Australian Museum, for alcohol-preserved voucher specimens. Specimens in collections like these are a critical resource for understanding our biodiversity.
CREDIT: WESTERN AUSTRALIAN MUSEUM

A day in the life of a biodiversity collection

The public faces of museums in Australia and New Zealand are the display galleries, education spaces and extension activities that provide public access to, and understanding about, parts of the museums' rich and varied collections. Few visitors, however, are aware that behind the scenes are much larger collections of scientific specimens that support research programs in taxonomy and biosystematics. Fewer still are aware of the important collections of plant specimens in herbaria, most of which have limited public access.

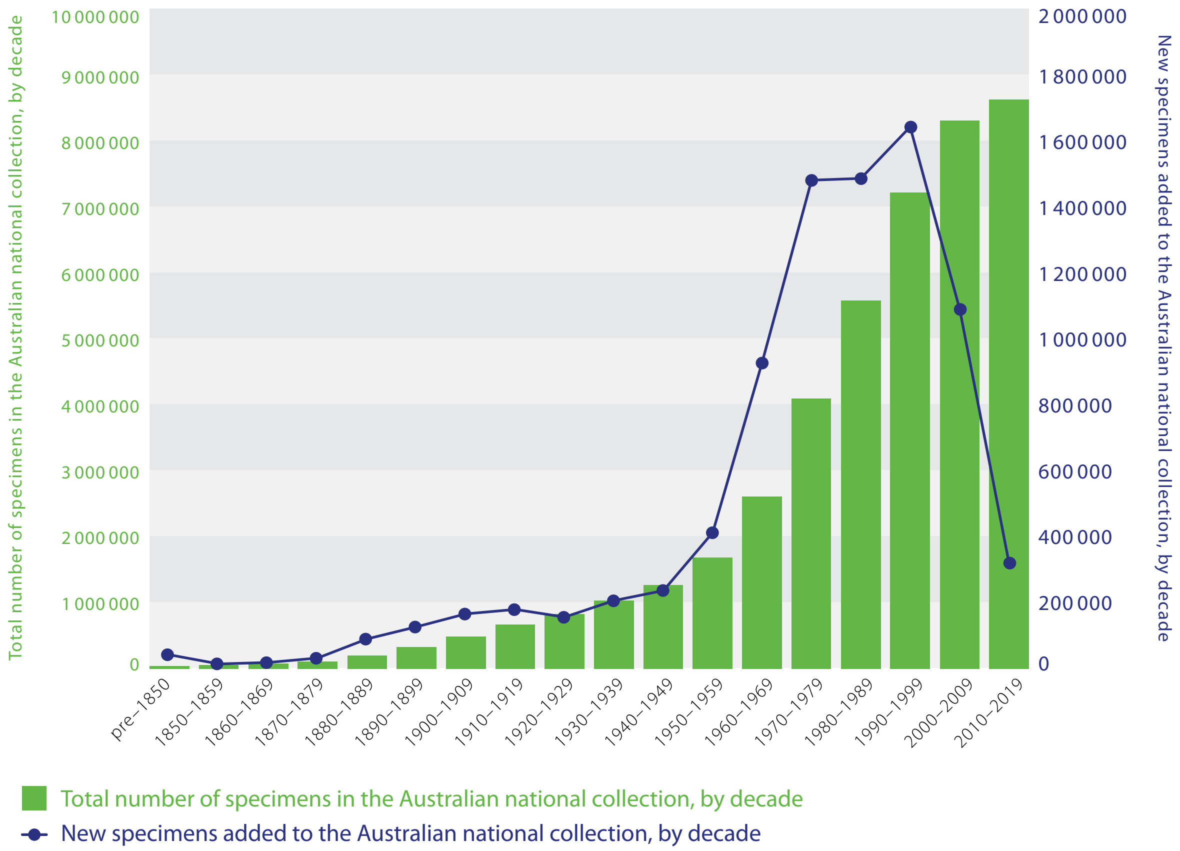
Biodiversity collections institutions in Australia and New Zealand are tasked with documenting faunal, plant and fungal diversity. To this end, staff at these institutions curate and study their collections of voucher specimens, both historical and modern. Specimens may be preserved in alcohol or formalin, dried or frozen as appropriate; the intention almost invariably is to preserve the specimens in perpetuity, as a permanent scientific repository of knowledge and research.

Specimens are accessioned into the collections as donations from members of the public, from field collections made during expeditions and trips, from external researchers vouchering specimens from research projects, and as gifts and exchanges from other institutions. Most museums and herbaria maintain general collections, as well as special-purpose collections to support the research of individual taxonomists. A small collection may comprise several thousand specimens; large ones will have many millions.

At any time, specialised curation staff process and preserve new accessions, database specimens, ensure that existing specimens are safe from damage, degradation or attack by pests such as museum beetles, store and retrieve specimens from the collection facilities for study by specialists including visiting scientists or researchers in other institutions, and keep the collection scientifically up-to-date and validated.

These activities, and the research conducted by the taxonomists who document, classify and name the specimens in the collections, often happen beyond the view of the public. Together, the work of collections staff provides some of our most fundamental understanding of Australian and New Zealand biodiversity.

Figure 8: Numbers of databased specimens added to the Australian national collection by decade



Numbers of databased specimens added to the Australian national collection, by date of collection. Growth in the collections peaked in the decade before 2000, and has declined since.[29]

Specimens in the collections cover all areas of the mainland and offshore islands and territories of Australia and New Zealand, the Antarctic Territories of both nations, and their surrounding seas and oceans.

In both Australia and New Zealand, collections grew rapidly from the 1850s to 2000. More than 1.6 million specimens were added in the decade 1990–1999. The rate of growth has since declined substantially: one-third fewer specimens were added in the decade 2000–2009 than in the preceding decade, a result of declining investment in collecting, and part of a world-wide trend.

This decline in investment in biodiversity collections will compromise future taxonomy and biosystematics, which will in turn compromise effective biosecurity and research into diverse areas such as the effects of climate change and other environmental stresses on biodiversity.

'Biological collections and databases, supported by world-class taxonomic expertise and research, provide the evidence base for New Zealand to respond effectively to present and future challenges.'

— Biosecurity 2025: Protecting to Grow New Zealand [30]

'The [lack of collecting] now will limit our ability to track responses to environmental change, at a time of major climate shifts with broad-reaching consequences for biodiversity.'

— *Gardner et al,* Frontiers in Ecology and the Environment [31]

29 Data are derived from the Atlas of Living Australia. Note that this figure includes only databased specimens; although most plant specimens in most herbaria are databased, only a fraction of animal specimens in museums are databased and captured here. However, changes in the rate of growth of the collection, including the decline since 2000, are likely to be an accurate reflection of actual numbers.

30 Biosecurity 2025: Protecting to Grow New Zealand (http://mpi.govt.nz/dmsdocument/14857-biosecurity-2025-direction-statement-for-new-zealands-biosecurity-system.pdf)

31 Gardner et al. (2014) Are natural history collections coming to an end as time-series? *Frontiers in Ecology and the Environment* 12: 436–438

The pectiniid hard coral *Mycedium elephantotus*, at rest with its tentacles retracted during the day.
CREDIT: JOHN HUISMAN

As well as documenting the known biodiversity of a region, state or nation, collections are key sources for discovery of new species: many specimens in the collections are of species that have not yet been studied, recognised, or documented as new. Even when potentially new discoveries are made in the field, recognising that a taxon is new would not be possible without the reference points provided by the known taxa in biodiversity collections.

New value is continually found for biodiversity collections, as they are repurposed for new methods and technologies such as next-generation DNA sequencing and isotope analysis, and new questions and challenges such as climate change and extinction research. The scientific value of collections is continually increasing. Today's collections underpin how we will understand and manage tomorrow's biodiversity.

Sequencing the Tasmanian tiger

All major biodiversity collections in Australia and New Zealand store tissue samples for genetic and genomic analyses, cross-referenced to voucher specimens. New technologies for extracting and sequencing DNA and assembling genomes from preserved samples also mean that almost the entire collection functions as a DNA bank. The recent sequencing of the complete genome of a Tasmanian tiger from a museum-preserved specimen[32] exemplifies this new use for biodiversity collections.

Carefully preserved specimens, such as this Tasmanian tiger (*Thylacinus cynocephalus*) pouch young, also preserve DNA, and can be used for genome sequencing.
CREDIT: BENJAMIN HEALLEY / MUSEUMS VICTORIA CC BY 4.0

32 Feigin et al. (2018) Genome of the Tasmanian tiger provides insights into the evolution and demography of an extinct marsupial carnivore. *Nature Ecology & Evolution* 2, 182–192 doi:10.1038/s41559-017-0417-y

New uses for old specimens

Rediscovery of the Lord Howe Island stick insect

The remarkable giant stick insect *Dryococelus australis* was once common on Lord Howe Island, but was driven to extinction after the arrival of ship rats in the early 20th century. It was believed to be globally extinct until a tiny population of giant stick insects was discovered on the nearby Ball's Pyramid in 2001.

However, comparison with museum specimens showed that the stick insects from the two islands were morphologically slightly different, raising the question as to whether the Ball's Pyramid insects are the same or a different species; if the latter is true, then the Lord Howe Island species remains extinct.

A group of Japanese and Australian researchers answered this question by sequencing the DNA from museum specimens collected on Lord Howe Island before its extinction there, and comparing these with sequences from the Ball's Pyramid insects. They showed that the two populations are indeed the same species. With a successful breeding program underway at Melbourne Zoo, the Lord Howe Island stick insect can now be reintroduced into suitable habitat on Lord Howe Island.

Museum collections were critical for taxonomic validation of the newly discovered population, and will support ongoing conservation efforts for this iconic species.

Tracking ozone recovery using mosses

Pollution of the atmosphere by industrial chlorofluorocarbons creates an ozone hole over Antarctica every summer. Loss of the protective ozone results in increased UV radiation, and associated increases in skin cancer and risks to animal and plant life.

Perhaps surprisingly, herbarium specimens of Antarctic mosses have proven to be a powerful research tool for monitoring the ozone hole.

Mosses protect themselves from UV radiation by producing their own sunscreens, in the form of flavonoid chemicals in their leaves. By studying the levels of these chemicals in moss specimens collected on the Antarctic Peninsula in different time periods, researchers have been able to track the development and subsequent recovery of the ozone layer. This use for Antarctic moss specimens was unimaginable when the first specimens were collected in the 1950s.

Although specimens—the physical infrastructure upon which taxonomy and biosystematics depend—remain foundational, digital representations of these specimens, ranging from databased records to high-resolution images, 3D scans, and genetic sequences, are also becoming increasingly important.

All major, and most minor, collections in Australia and New Zealand are at least partially databased. Australia and New Zealand have been world leaders since the earliest days of the World Wide Web in making biodiversity data available online. The value of databasing specimens has been demonstrated by the success of the Australasian Virtual Herbarium, an online resource that provides access to maps and records of more than six million specimens from all major Australian and New Zealand herbaria.

Collections throughout the world are digitally imaging their specimens, and high resolution images are becoming increasingly important research tools. In many cases the images can be studied online in preference to handling the physical specimens, which enhances research, reduces costs associated with loaning specimens and increases security for often priceless specimens. Such images are also being used in crowdsourcing projects to digitise the label information. Australia and New Zealand are lagging behind other countries such as the US and Europe in digitising collections in this way.

The moss *Racomitrium pruinosum*, which is widespread in the Southern Hemisphere.
CREDIT: DAVID GLENNY

The Atlas of Living Australia

The Atlas of Living Australia (ALA) provides online e-research infrastructure to support the capture, aggregation, management, visualisation and analysis of biodiversity data for research, industry, government and the community. The ALA aggregates more than 12 million vouchered records from Australian and New Zealand museums and herbaria. These core vouchered records join more than 60 million unvouchered records (records of an observation of an organism at a place and time). Records can be mapped, analysed using online spatial tools, or downloaded for more detailed analyses.

In addition to occurrence records and maps, the ALA aggregates and provides access to images of Australian organisms from online image banks, key information on classification and nomenclature, and access to relevant online literature.

Records from the ALA have been downloaded over 1.6 million times since 2010, by researchers, government departments and members of the general public, for analyses, including modelling the potential distributions of invasive pests and diseases, understanding the likely impacts of climate change on rare species, creating local flora and fauna guides for school children, and allowing the public to assess what species occur in their local neighbourhood.

The ALA is a core component of biodiversity infrastructure in Australia. It is also well-positioned internationally, with linkages to key global biodiversity information initiatives. Its tools and infrastructure are now being used to support national biodiversity portals in 10 countries. The ALA is funded by the Australian Government under the National Collaborative Research Infrastructure Strategy (NCRIS), and managed by CSIRO.

The Australasian Virtual Herbarium and OZCAM

Australian and New Zealand herbaria and museums were early adopters of computer technology, databasing specimens as soon as computers became readily available. Beginning in 1985, world-leading systems were developed to enable digital records to be shared and aggregated between herbaria. This led to the development of the Australian (now Australasian) Virtual Herbarium (AVH), which brings together and makes accessible more than six million specimen records from all major Australian and New Zealand herbaria, and Online Zoological Collections of Australian Museums (OZCAM), which mobilises nearly 5 million specimen records from Australian museums. These were precursors to the Atlas of Living Australia (ALA), which aggregates records from all collections and from non-vouchered observations.

The AVH, OZCAM and ALA demonstrate the value of collaboration between collections institutions, working together to pool their data for the common good. No other country or region of the world has a more advanced system for providing open access to key biodiversity knowledge from collections.

In contrast to plant specimens in herbaria, most animal specimens in museums are not databased. Crucial data about the specimens, such as their location and date of collection, and about the species they represent, are largely unavailable for biodiversity analyses and other purposes. Although undatabased specimens are still extremely important, they are largely inaccessible outside their institution.

2.4 Our people

The Australian community of taxonomists and biosystematists comprised 335 full-time equivalent (FTE) positions in November 2017, mostly employed at State museums, herbaria and universities. In New Zealand, the community comprised 110 FTE in 2015[33], mostly employed at Crown Research Institutes and museums.

There has been a 10 per cent decline in the taxonomic workforce in major collections institutions in Australia during the past 25 years, from 377 FTE in 1991 to 335 FTE in 2017, with a slightly greater decline in the museum than the herbarium sector[34]. During this time the Australian population increased by 40 per cent, and GDP more than doubled in constant dollar value.

New Zealand had a very substantial reduction in the taxonomic workforce between 1995 and 2001, with a 60% reduction in the Crown Research Institutes and Universities during those five years. Similarly, the taxonomy and biosystematics workforce in the museum sector declined by 22% in the period 2001–2015.

In both countries there is a trend towards higher proportions of older workers, consistent with a resource-constrained sector with few new job opportunities.

In 2015, 16 per cent of the New Zealand taxonomic workforce were in the 20–40 age bracket; the situation in Australia is slightly better, with 19 per cent in that bracket.

In Australia, a quarter of the total workforce comprises unpaid, retired or honorary associates, mostly previously employed taxonomists who continue to work in the field after retirement. This proportion has increased over time (from 19 per cent in 1975 to 25 per cent in 2016), concomitant with the overall ageing of the workforce. New Zealand has a similar proportion of retired and hence unpaid taxonomists in the total workforce. Although the continued productive activity of retired taxonomists is clearly to be welcomed and increases total output of the sector, it presents substantial risks for future sustainability, and indicates that an increasing proportion of taxonomic productivity is unpaid.

As with other sectors of the workforce, there is a trend towards fixed-term, short-term and part-time positions and away from full-time permanent positions. In Australia, 74 per cent of the taxonomic workforce were in full-time permanent positions in 1975 compared with 43 per cent in 2016. In New Zealand, 45 per cent of the workforce were in short term positions in 2015. This is particularly counterproductive in a sector such as taxonomy where outputs increase with long-term knowledge, experience and specialisation.

Collecting insects, Henbury Station Bush Blitz, Northern Territory.
CREDIT: JO HARDING / © COMMONWEALTH OF AUSTRALIA.

33 Based on the report National Taxonomic Collections in New Zealand (http://royalsociety.org.nz/assets/Uploads/Report-National-Taxonomic-Collections-in-New-Zealand-2015.pdf)

34 Based on surveys compiled by the Australian Biological Resources Study in 1991, 2003 and 2017.

The workforce is 63 per cent male in Australia and 65 per cent in New Zealand; gender equality has improved slightly over the past three decades (it was 77 per cent male in Australia in 1991). However, as in many other sectors, more women than men work in non-permanent, part-time, and casual positions, and this has negative consequences for their career paths and prospects.

In 1975, there were more taxonomists in the 30–39 year age category than any other. In 2017, the 40–44 year category was the largest for females and the 55–59 year category was the largest for males.

Compared with other countries, investment in Australian and New Zealand taxonomy and biosystematics (measured by the number of staff in institutions) is modest. The combined workforce in herbaria in Australia and New Zealand (332 people) is significantly less than in Mexico (368), India (401), Argentina (490), Brazil (819) and China (1 270), despite an equivalent or higher GDP and biodiversity than most of these countries.

Of the employed workforce, only a small proportion spend most of their time on taxonomic research. In New Zealand, 77 per cent of publicly funded taxonomists spend less than 25 per cent of their time on taxonomic research, and over half (60 per cent) spend less than 10 per cent; the remaining time is spent in administrative tasks, answering public queries, education and extension. The situation in Australia is better, with 45 per cent of taxonomists spending less than 25 per cent of their time on taxonomic research, and 30 per cent spending less than 10 per cent of their time. These figures indicate that highly qualified taxonomic research skills are underutilised, particularly in New Zealand, risking an erosion of capability through loss of currency of knowledge and skills.

Expertise in two taxonomic groups, flowering plants and arthropods (e.g. insects and crustaceans), dominates in both Australia and New Zealand. By comparison, many other groups of organisms (e.g. nematodes, sponges, bacteria) have very few taxonomic experts.

A botanical intern on field work in New South Wales.
CREDIT: BRONWYN COLLINS / © CENTRE FOR AUSTRALIAN NATIONAL BIODIVERSITY RESEARCH.

Sampling feathers from specimens, to extract DNA for taxonomic and biosystematic studies, Western Australian Museum.
CREDIT: CLAY BRYCE / WESTERN AUSTRALIAN MUSEUM

The remarkable megaherbs of New Zealand's Campbell Island - *Pleurophyllum speciosum*, with *Bulbinella rossii* and *Anisotome latifolia*.
CREDIT: PHIL GARNOCK-JONES

2.5 Current investment

Total annual funding for taxonomy and biosystematics in Australia is estimated at A$43.6 million. Over 70 per cent of funding comes from state governments, mostly in the form of operational and staff costs for state museums and herbaria. 21 per cent of funding is from the Commonwealth, mostly for operational and staff costs for the CSIRO collections but including research and salary funding directed to the states through ABRS.

Over 86% of investment is non-discretionary (salaries, facilities running costs); ten per cent of total funding (A$4.3 million) comprises direct research funding. The Australian Biological Research Study (ABRS) provides A$2 million per annum for taxonomic research through its National Taxonomic Research Grants Programme (NTRGP), with an extra A$4 million made available during the past eight years through the government–industry Bush Blitz partnership. ABRS and the NTRGP were pivotal to the step change in biodiversity productivity that occurred in the early 1970s, and will remain critical for the successful implementation of this plan.

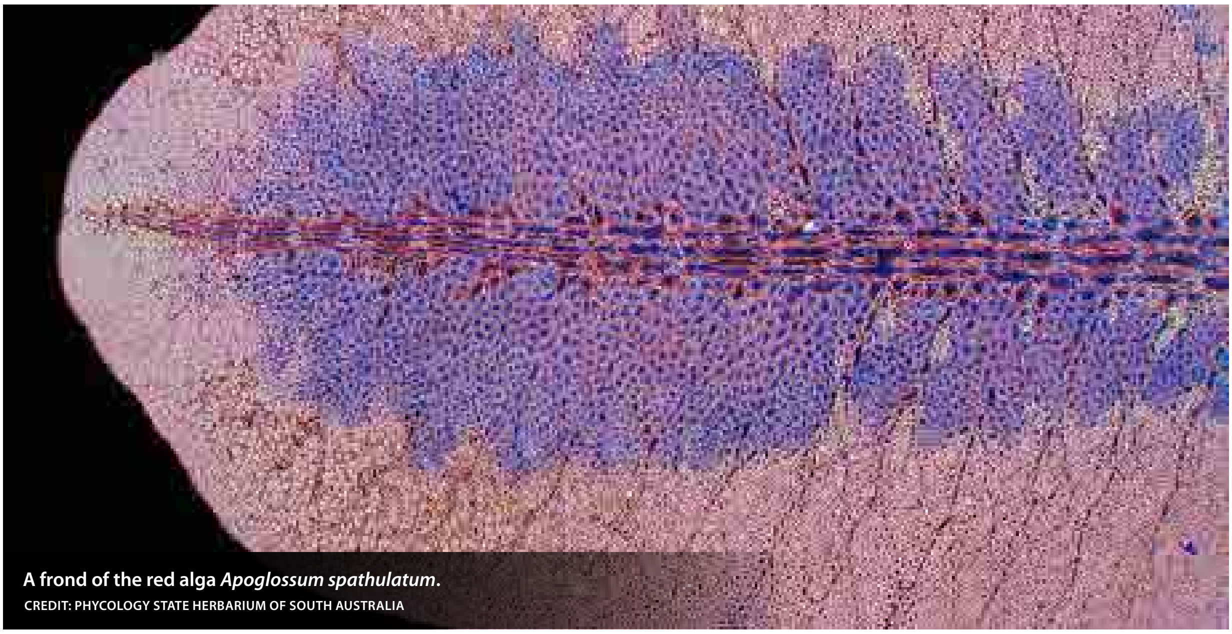
National Collaborative Research Infrastructure Strategy (NCRIS) funding has supported taxonomy and biosystematics indirectly, by establishing important capabilities such as the Atlas of Living Australia (ALA) and BioPlatforms Australia (BPA). The ALA, as an aggregator of biodiversity records and other data, has become key infrastructure for the sector, but does not create new taxonomic knowledge or directly support the maintenance of other key infrastructure such as biodiversity collections. BioPlatforms Australia supports key genomic data streams and the maintenance of genomic data, and is supporting a small number of genomic projects with direct relevance to taxonomy and biosystematics including genome-sequencing programs for Australian marsupials and flowering plants.

In New Zealand, it was estimated in 2015[35] that NZ$12.5 million was being spent annually to cover staffing, materials, housing and overheads in the larger biodiversity collections. Investment in New Zealand comes from a variety of sources. Each organisation has a primary funding source, which may be supplemented by secondary sources.

Crown Research Institutes (CRIs) receive the majority of their funding, for both research and collection management, from the Strategic Science Investment Fund administered by the Ministry of Business and Innovation (MBIE). However, costs are increasing while available funding has remained static

35 National Taxonomic Collections in New Zealand, https://royalsociety.org.nz/assets/Uploads/Report-National-Taxonomic-Collections-in-New-Zealand-2015.pdf (or had only minor increases) for more than a decade. The Cawthron Institute also receives non-contestable funding under a contract from MBIE. The Museum of New Zealand Te Papa Tongarewa receives funding from the Ministry for Culture and Heritage, with additional funds from external sources used to enhance its taxonomic and biosystematics research programs. Regional and metropolitan museums in New Zealand receive core funding from local government, supplemented by sponsorship and other grants or endowments. Research and collections at universities are primarily funded through the Performance-Based Research Fund administered by the Tertiary Education Commission.

New Zealand has no funding sources equivalent to the Australian ABRS, which directly targets investment into taxonomic and biosystematic research. Nor are there direct equivalents of the Australian NCRIS programs in New Zealand, which provide infrastructure to support biodiversity research. However, the importance of taxonomy and biosystematics as national science infrastructure is recognised by the designation of the CRI and Cawthron Institute taxonomic collections as Nationally Significant Databases and Collections. The importance of maintaining and building taxonomic collections infrastructure, including making the data held in these collections available, is highlighted in a "Biosecurity 2025" report currently being prepared by the Ministry of Primary Industries.



A frond of the red alga *Apoglossum spathulatum*.
CREDIT: PHYCOLOGY STATE HERBARIUM OF SOUTH AUSTRALIA

Examining a specimen of Sturt's desert pea *Swainsona formosa*.
CREDIT: © CSIRO

Children love dinosaurs, a great entry point into learning about biodiversity and the history of life on Earth.
CREDIT: WESTERN AUSTRALIAN MUSEUM

3 Education and training

THE FUTURE OF LIFE ON EARTH MAY DEPEND ON THE PEOPLE WHO LEARN ABOUT NATURE AND ITS SPECIES TODAY.

Education is central to human understanding of the environment, and human understanding of biodiversity is becoming increasingly central to the health of the biosphere. An engaged, educated and informed public provides a buffer against decisions that cause environmental degradation and species extinction, and encourages governments to use natural resources wisely and for maximum benefit. Ensuring a strong connection to the natural environment is becoming increasingly important with increasing urbanisation. The future of life on Earth may depend on the people who learn about nature and its species today.

Education is also the key to a sustainable future taxonomic workforce that can realise the opportunities, and meet the challenges, of the future. Many students, both from Science, Technology Engineering and Maths (STEM) and non-STEM backgrounds, have a natural affinity to biodiversity, an affinity called *biophilia*[36]. Education needs to augment this by providing training in the new approaches and ground-breaking methods that are critical if we are to document our rich biodiversity.

Education about biodiversity, and in taxonomy and biosystematics, occurs at schools, at universities, in institutional workplaces and, through citizen science, across a broad cross-section of the community.

The gorgonian sea fan *Ctenosella pectinata*.
CREDIT: JOHN HUISMAN

Many species of living things are still to be classified. This peacock spider from Western Australia was previously known as *Saitis speciosus* but has now been included in *Maratus*.
CREDIT: JURGEN OTTO / FLICKR CC BY-NC-ND 2.0

36 Wilson, E.O. (1984) *Biophilia*. (Harvard University Press: Cambridge, London)

3.1 Taxonomy and biosystematics in schools

All Australian and New Zealand schools introduce biology, including classification and the diversity of organisms, early in the science curriculum. The affinity children have with living organisms means that biodiversity provides a unique portal into an understanding of the natural sciences as a whole, and is important as an engaging introduction to STEM and science literacy in general.

Students learn that living things have a variety of external features, and that these are a key to understanding them and their relationships. This is later augmented by a more formal introduction to classification—the grouping of living things on the basis of their features. Classification is a core activity of all sciences, from chemistry to astronomy, and an introduction to classification through biodiversity establishes an important foundation for other sciences.

In later primary and high school curricula, these core concepts (classification, critical observation, and analysis of features) are used to explore evolution, the key explanatory framework for life and biodiversity. Again, the connection and fascination children have with living and extinct organisms provides an important bridge to a key concept in the whole of science—that simple causal factors underlie complex patterns of diversity.

Among the Gumtrees and Curious Minds: Introducing primary school students to identification and taxonomy

Among the Gumtrees is a Year 4 science curriculum unit developed by the Australian Academy of Science and the philanthropic trust Eucalypt Australia. A practical, step-by-step lesson guide, Among the Gumtrees supports students to develop knowledge and understanding of Australia's iconic eucalypts, and skills in both science and literacy.

Through hands-on investigations, students identify eucalypts around their school grounds, explore the fruit and flowers of eucalypts, learn how different living things interact with gumtrees, and plan and conduct experiments.

Curious Minds is a New Zealand Government initiative with a ten-year goal of encouraging and enabling better engagement with science and technology for all New Zealanders, including students. Projects include biodiversity surveys of seashore sand reefs, investigations of moth diversity in and around Otago, and discovering mushrooms and their relatives by reconnecting students with Māori knowledge about fungi.

Both Among the Gumtrees and the biodiversity projects in Curious Minds connect students and others with knowledge of the biodiversity of a region. This connection both nurtures, and is dependent on, the knowledge of biodiversity provided by taxonomy and biosystematics.

School children often visit biodiversity collections to learn about the natural world. Here children are shown specimens in the Allan Herbarium, Christchurch.
CREDIT: AARON WILTON

3.2 Graduate and postgraduate studies in taxonomy and biosystematics

Many students in Australia and New Zealand take first-year biology subjects, where they deepen their understanding of biodiversity and of the classification and evolution of life, and gain exposure to fields such as genetics, cell biology, behaviour, ecology and physiology. All of these are underpinned by taxonomy and biosystematics.

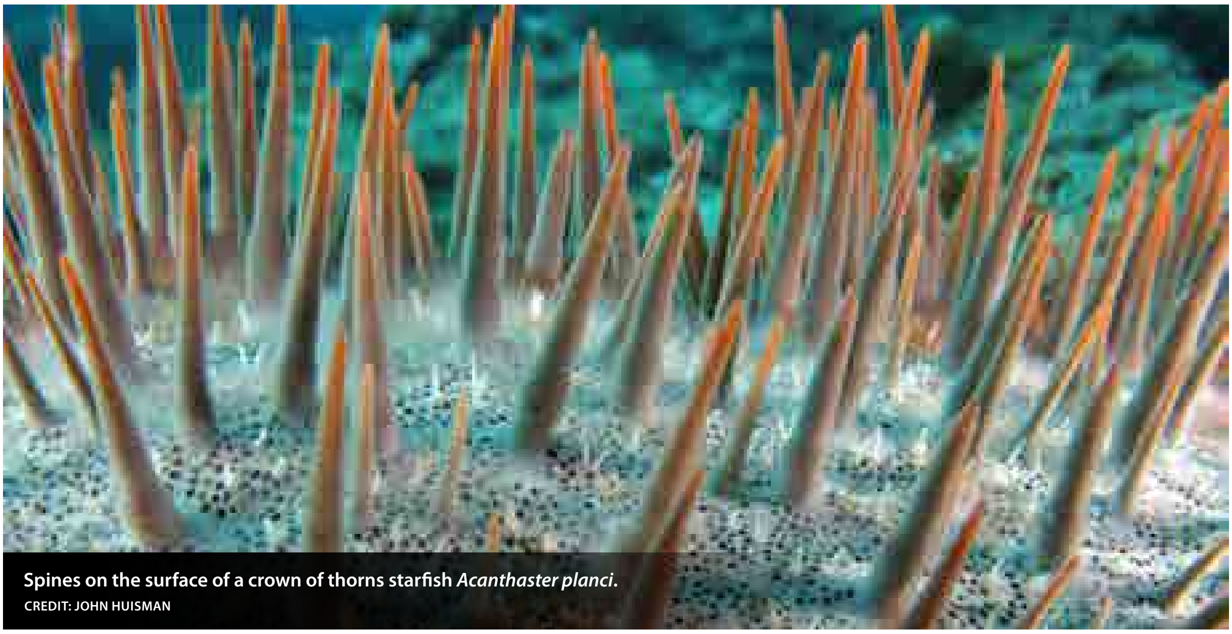
Although taxonomy and biosystematics play a role in first-year biology, only nine Australian and seven New Zealand universities offer specialist second- and third-year units in taxonomy, biosystematics and organismal diversity, and teaching at these levels has declined in recent decades. Students retain a strong interest in biodiversity studies, including taxonomy and biosystematics, but course limitations discourage them.

Ten universities in Australia and seven in New Zealand offer postgraduate projects in taxonomy and biosystematics.

Graduates with a sound training in taxonomy and biosystematics and a good familiarity with biodiversity are highly employable in areas outside of professional taxonomy, such as biosecurity, agriculture, ecological sciences, conservation planning, land management and environmental impact assessment.

A key task, however, is ensuring that talented students who wish to pursue a career in taxonomy and biosystematics have an opportunity to do so, equipping them with the broad range of skills needed in modern taxonomy and biosystematics. One way to do this is to integrate and link teaching resources across universities, and between universities and collections institutions, to ensure that students have access to the best expertise wherever it may be.

Studying specimens at the Australian National Insect Collection.
CREDIT: © CSIRO



Spines on the surface of a crown of thorns starfish *Acanthaster planci*.
CREDIT: JOHN HUISMAN

Botanical trainees pressing newly collected plant specimens as part of field training.
CREDIT: BRONWYN COLLINS / © CENTRE FOR AUSTRALIAN NATIONAL BIODIVERSITY RESEARCH

3.3 In-service training and professional development

Taxonomy and biosystematics are rapidly changing disciplines. The ongoing revolution in methods, concepts and technologies has two consequences: firstly, the taxonomic and biosystematics workforce needs in-service training to make best use of new opportunities and methods; and secondly, other biodiversity professionals such as industry consultants and biosecurity diagnosticians need ongoing training to keep abreast of taxonomic changes and new technologies in their fields of expertise.

In-service training in taxonomy and biosystematics is not well developed in Australia or New Zealand. Partnerships among taxonomy and biosystematics research institutions, the university sector, Indigenous peoples and industry groups are needed to address this.

Within any discipline, new entrants bring new ideas, but sometimes lack the experience needed to work effectively. Two-way, formal mentorships, where experienced taxonomists mentor new entrants in core concepts and knowledge, and new entrants mentor experienced taxonomists in new methods, will bring substantial benefits within the discipline. Formal mentorship programs are not well established in Australia or New Zealand.

3.4 Citizen science, community literacy, engagement and participation

For many people, the universal childhood fascination with the living world continues into adulthood and provides impetus for lifelong learning. Facilitating such learning enhances bioliteracy, a familiarity with and appreciation of biodiversity. Bioliteracy is likely to be fundamental to a sustainable society: people value only what they know and can relate to.

Citizen science, the collection and analysis of data relating to the natural world by members of the public, has great potential in Australia and New Zealand. Levels of engagement with the natural world are relatively high compared with many countries. Our relative wealth provides a substantial resource in people's time and energy, and our rich biodiversity means there is a high need.

Most biodiversity-related citizen science projects provide ways for members of the public to contribute observations (e.g. photographs and sightings) of organisms. The Atlas of Living Australia supports over 550 citizen science projects through its Citizen Science Project Finder[37], including censuses of iconic species such as platypus and black cockatoos, local or regional surveys and bioblitzes, and local, regional and national general observational projects. In New Zealand, NatureWatch[38] aggregates observations of organisms from over 5 000 recorders, with more than 2 000 specialists, ranging from professionals to knowledgeable amateurs, helping to identify contributed images.

Contributions of observational records may help extend knowledge of the distributions and status of recognised taxa, but are rarely directly connected to taxonomy and biosystematics. Exceptions are cases where, for example, contributions of photographs to platforms such as Museum Victoria's Bowerbird[39] have resulted in the serendipitous discovery of new species when reviewed by taxonomic experts.

Of more direct relevance is the DigiVol portal managed by the Australian Museum and ALA. This supports over 1 000 'expeditions'—projects that crowdsource the digitisation of biodiversity collections, transcription of field books, and assessment of camera trap photographs to name a few. DigiVol is used by collections institutions throughout the world, and contributes significantly to efforts to mobilise otherwise inaccessible collection records and other data.

Many DigiVol expeditions crowdsource the transcription of label information from digital images of museum and herbarium specimens. However, this remains a challenging and time-consuming process, leading to attempts to automate it. In 2015, a US$1 million prize was offered for the creation of a technology that increases the speed and accuracy of digitisation of a drawer of insect specimens and their associated data. No entries were received. Digitisation of museum collections remains a hard problem.

Few citizen science projects anywhere in the world have been established specifically around taxonomy and biosystematics projects. An opportunity exists, particularly in Australia and New Zealand where so much taxonomy remains to be done, for broader involvement of citizen science in taxonomy and biosystematics.

Examples of citizen science projects in Australia and New Zealand

QuestaGame[40]—a real-world mobile game in which participants compete to save life on Earth.

NatureWatch[38]—a platform where keen observers can record what they see in nature, meet other nature watchers, and learn about the natural world.

Ahi Pepe | MothNet[41]—a citizen science project that aims to engage teachers, students and whānau with moths, and through moths with nature and science.

A rarely collected and taxonomically poorly understood but spectacular Australian fungus in the genus *Arrhenia* (possibly *A. chlorocyanea*).

CREDIT: JOHN EICHLER

37 https://biocollect.ala.org.au/acsa

38 http://naturewatch.org.nz

39 http://bowerbird.org.au/about

40 https://questagame.com/home

41 https://landcareresearch.co.nz/information-for/citizen-science/mothnet

The diatom *Pleurosigma angulatum*. Diatoms are unicellular, photosynthetic micro-organisms found in many aquatic and marine habitats. They are very diverse, ecologically very important, and taxonomically poorly documented.

4 Opportunities and challenges

THE AUSTRALIAN AND NEW ZEALAND TAXONOMY AND BIOSYSTEMATICS COMMUNITIES HAVE A SOLID FOUNDATION, AND WITH APPROPRIATE INVESTMENT AND SUPPORT CAN TAKE UP OPPORTUNITIES, AND MEET CHALLENGES.

The decade 2018–27 will bring opportunities and challenges for the discovery and documentation of Australia's and New Zealand's biodiversity. Opportunities arise mostly from new and developing technologies, and challenges from the magnitude of the task and the social environment in which we operate.

A better understanding of Australia's and New Zealand's unique and rich biodiversity will improve human health, enhance manufacturing, industry and food production, support conservation, and help underpin the sciences of life. As transformative genomic and other technologies continue to develop, the Australian and New Zealand taxonomy and biosystematics communities are strongly placed to realise their potential over the coming decade.

As well as opportunities, significant cultural, social, scientific and technological challenges will need to be addressed if we are to enjoy current and future benefits from our region's diverse biodiversity.

The Australian and New Zealand taxonomy and biosystematics communities have a solid foundation, and with appropriate investment and support can take up these opportunities, and meet these challenges, in one of the richest, most diverse and most important regions in the world.

Red-tailed tropicbird, *Phaethon rubricauda*. Coral Sea, Queensland, Australia.
CREDIT: RYAN SCHOFNER

4.1 The genomics revolution

Genome sequencing is playing an increasingly important role in discovering and delimiting species and other taxa, identifying specimens, and building the phylogenies (evolutionary trees) on which modern classification systems are built. Steady, and sometimes dramatic, improvements in these methods are leading to a dramatically increasing amount of information available for taxonomic and biosystematic studies.

Genomic methods also provide unique opportunities for environmental DNA (eDNA) studies—sequencing and analysing DNA in soil, water, air and other bulk environmental samples. These studies indicate the presence of so-called 'biodiversity dark matter'—whole branches of the tree of life that have been hitherto invisible, and contain significant biodiversity and many new species.

Although these methods can indicate the presence of new species, these can rarely be characterised, named, classified or placed accurately in the evolutionary tree of life. This is partly because an adequate library of well-curated reference sequences for most known species is currently lacking, and partly due to limitations in current genomic methods and analyses.

Given the pace of technological change, these methods and their supporting data will improve dramatically in the next decade. The taxonomy and biosystematics community will play a key role in ensuring that the full potential of these technologies can be realised and exploited.

Biodiversity dark matter

Many of the species that have not yet been recognised have also never been seen by biologists, even though they may be living all around us, or even in us. These represent so-called 'biodiversity dark matter'—organisms that cannot be detected using traditional methods.

Bacteriologists, for example, have traditionally grown bacterial colonies on agar plates, and this has been a key step in the discovery and documentation of species to date. However, species that will not grow under laboratory conditions are 'invisible' to such methods.

New approaches developed in the past decade, utilising powerful new genetic and computing methods, have allowed taxonomists to discover new species from DNA alone. DNA is extracted directly from soil or water, gut samples, deep rocks or the deep ocean, or elsewhere in the environment, and sequenced in small fragments. The fragments are then assembled into larger gene or genome sequences, using supercomputers. These methods have opened a new window on biodiversity, and revealed very large numbers of hitherto invisible species, particularly in microscopic groups such as bacteria, protists, nematodes and fungi.

Understanding the taxonomy and evolutionary history of biodiversity dark matter is important for many reasons. As well as being abundant, hyperdiverse and ecologically important, some dark matter organisms, particularly bacteria and the intriguing bacteria-like group called Archaea that occur deep within the Earth's crust, around deep-ocean hot springs and in other extreme environments, may hold the key to one of the deepest questions in all science: How did first life evolve? Biodiversity dark matter, like its cosmological equivalents physical dark matter and dark energy, may lie at the heart of some of the biggest scientific questions of this century.

4.2 Imaging biodiversity

Imaging has always played an important role in taxonomy and biosystematics, from the earliest publications using woodcuts and copperplate engravings of new species to the present. Digital imaging has revolutionised our ability to study, illustrate, and analyse biological structures and specimens.

Scientists around the world can now access and study high-resolution digital images of important specimens without needing to travel or physically borrow them. The Global Plants project, which provides online access to critical type specimens from major herbaria throughout the world, has made Australian and New Zealand taxonomic botany substantially more efficient, faster and more effective.

3D imaging has also revolutionised studies of animal specimens and fossils. X-ray computer tomography (CT) scanning and synchrotron beam imaging allow specimens to be imaged in exquisite detail without damaging them, even, in the case of fossils, while still encased in rock. This opens new avenues for comparison and sophisticated statistical analysis, which in turn is leading to the discovery of new species and enhanced understanding of existing species.

Some biodiversity institutions are now imaging their entire collection. The Paris Herbarium, for example, has imaged its entire holdings of more than seven million specimens, using a high-throughput conveyor system and automated digital imaging. The National Science Foundation-funded iDigBio program in the US has digitised more than 23 million of the nearly one billion specimens in US biodiversity collections. These images are being used for crowdsourcing of specimen information and research projects throughout the world.

In Australia and New Zealand, imaging of specimens and collections is in its infancy, but holds great promise.

A microscopic computed tomography (micro-CT) scan of a female mygalomorph spider (*Bertmainius* sp.). CT scans are helping taxonomists better understand the detailed external and internal features of specimens.

CREDIT: NIK TATARNIC / WESTERN AUSTRALIAN MUSEUM

4.3 Bioinformatics and machine learning

Taxonomists and biosystematists have always been early adopters of new technologies. Taxonomists were among the first to explore newly invented optical microscopes in the 17th century and electron microscopes in the 20th, and were early adopters of computers for analysis and databasing. Some of the first websites on the newly invented internet were developed by taxonomists to allow public access to biodiversity records in collections.

Along with the genomics revolution, the next decade will see rapid advances in computing, particularly in big data, artificial intelligence and machine learning, and these will provide new opportunities for taxonomy and biosystematics.

Big data is core business for taxonomic and biosystematics research, and will grow substantially over the next decade. Digitisation of specimens and specimen records, and genomic data made available through, and analysed for, taxonomic and biosystematic studies, comprise a massive global data resource.

The complexity of taxonomic patterns, and the requirement to analyse very large datasets to elucidate these patterns, lends itself to machine- and deep-learning approaches. These approaches need to be embraced in the next decade.

Importantly, rigorous quality control is needed for these data and these innovations to reach their potential; poor-quality data leads to poor quality results. Careful curation—that is, rigorous quality control—is also core business for taxonomy and biosystematics. Sufficient capacity is needed at all levels of the taxonomy and biosystematics business, from specimen management to data management, if the opportunities of bioinformatics, machine learning and big data are to be realised.

4.4 The connected world

Connectivity in taxonomy and biosystematics is high. In many ways, the world's first truly global, interconnected science was taxonomy: the Linnaean system of binomial nomenclature was universally adopted in the mid-18th century, well before there were global systems of measurement, time or calendars.

With the global reach of the internet, opportunities for collaboration in taxonomy and biosystematics are growing rapidly. Large-scale international collaborations are building big-science taxonomy and biosystematics collaborations on a scale previously unachievable.

Australia and New Zealand need to be part of these collaborations, as economically wealthy nations that hold globally significant biodiversity, including lineages of organisms that are key to understanding evolution, and as partners that stand to benefit from early adoption of new international technologies.

Global biodiversity in a connected world

Australia is a key partner in many major international biodiversity initiatives, including:

- **The Global Biodiversity Information Facility (GBIF)** – a global equivalent of the ALA that has aggregated nearly a billion specimen and high-quality observational records from 36 000 institutions and datasets
- **The Encyclopedia of Life (EoL)** – a US-led initiative that aims to create a web page for every species on Earth
- **Global Plants** – the world's largest online database of digitised plant specimens and a locus for international scientific research and collaboration
- **World Flora Online** – an ambitious project to create an online resource for all the world's plants, established under the UN Convention on Biological Diversity
- **The Oceanographic Biogeographic Information System (OBIS)** – a global open-access data and information clearing-house on marine biodiversity for science, conservation and sustainable development
- **Genome 10K** – which aims to assemble a genomic zoo—a collection of DNA sequences representing the genomes of 10 000 vertebrate species, approximately one for every vertebrate genus
- **1KITE** – a consortium of 11 countries, including Australia and New Zealand, which aims to study the expressed genes of more than 1000 insect species encompassing all recognised insect orders, in order to reconstruct their evolution and to better understand the biology of pests.

4.5 Extinction

Many scientists regard that the Earth has entered a new epoch, the Anthropocene. Like other transitions between geological eras, the marker for this transition is a mass extinction event, though uniquely this one is avoidable and human-induced.

The current rate of species extinction is estimated to be 10–1 000 times higher than the natural, background rate, and this is likely to climb as habitat destruction, global change and other human-induced stresses on the natural environment accelerate. The very wide range in this estimate is a result of taxonomic uncertainty: we currently have only poor estimates of the number of species on earth, and most extinctions probably occur in poorly studied groups such as insects in tropical rainforests and marine invertebrates. The gaps in our taxonomic knowledge, both globally and in Australia and New Zealand, mean that we cannot even accurately assess the scale of the problem, yet such an assessment is a crucial first step towards addressing it.

Whatever the actual rate, it is unavoidable that many species will be lost before they are known, especially in less-studied groups. While naming and documenting a species will not in itself prevent its extinction, it is an important first step, and is a requirement for legal protection. The knowledge that comes with taxonomic documentation, of distribution, habitat, and abundance or rarity, plays an important part in conservation planning for species and areas. Taxa that are undocumented are more likely to be lost, and lost without knowledge of their loss.

4.6 Hyperdiversity

Some taxonomic groups, particularly bacteria, fungi, nematodes, mites and some insect groups, such as beetles, wasps, ants and moths, are hyperdiverse, each estimated to comprise hundreds of thousands to millions of species, many of which have not yet been discovered. These groups are particularly challenging for taxonomy and biosystematics. When faced with hyperdiversity, business-as-usual is not good enough.

Fortunately, new methods and technologies can help deal with hyperdiverse taxa. The genomic revolution has the potential to accelerate species discovery, and the hyper-connectivity of the modern world—coupled with new opportunities for rapid, electronic publication—can substantially increase the rate at which newly discovered species are named and documented.

A strategic approach is necessary to resolve these hyperdiverse groups, gaining the maximum benefit from effort to ensure that the hyperdiversity problem becomes tractable as quickly as possible.

The common blue-banded bee *Amegilla chlorocyanea*. Males of this species are solitary, and rest overnight by clinging to plant stems using their mandibles.
CREDIT: FRED AND JEAN HORT

Microscopic fungi are hyperdiverse. This recently-discovered species is un-named and is a "dark matter" organism - its classification and relationships are very uncertain.
CREDIT: JERRY COOPER / MANAAKI WHENUA - LANDCARE RESEARCH

4.7 Community perceptions of taxonomy

The disciplines of taxonomy and biosystematics were held in high regard in scientific circles in the 18th and 19th centuries, when documentation of the world's biodiversity was a key scientific endeavour. Charles Darwin, one of the world's most influential scientists, was a taxonomist, whose theory of evolution arose directly from his taxonomic studies.

Since the mid-20th century, the standing of taxonomy in the science community has fallen, with some regarding it as being only marginally scientific.

Moreover, taxonomy is regarded at times as a 'nuisance', because a new understanding of evolutionary relationships sometimes requires the renaming or reclassification of taxa. The tension between the desire for a stable, convenient taxonomy on the one hand, and a robust, evidence-based one on the other, is a challenge both for taxonomists and for end users.

A fascination with the discovery of new species, especially those that have a quirky element or are named after a celebrity, gives taxonomy and biosystematics some public profile. However, the patient management and curation of collections that enables such discoveries, the detailed knowledge required to be able to recognise a species as new, the scientific rigour and hypothesis testing that underpins species recognition, and the care that must be given to species naming and characterisation, are rarely foregrounded. Discoveries are portrayed as eureka events, with scant attention to the career(s) that enabled the eureka to happen.

In this sense, taxonomy is similar to many other sciences. It faces the modern trend towards devaluation of expertise in favour of democratised knowledge. This is most apparent in the exaggerated claims made by developers of commercial identification apps—that anyone with a mobile phone can now identify any taxon. If this were the case, there would be no need for taxonomists; it is not the case.

A challenge and opportunity for this decadal plan is to change, and seek to reverse, these perceptions.

Salmon gum (*Eucalyptus salmonophloia*) in Western Australia's Great Western Woodlands. The iconically Australian eucalypts are taxonomically very diverse, with nearly 900 species and more discovered every year.
CREDIT: SUZANNE PROBER

A southern bobtail squid *Euprymna tasmanica*. *Euprymna* squids occur from Australia to Japan, with several taxonomically poorly resolved species.
CREDIT: MUSEUMS VICTORIA CC BY 4.0

An echidna (*Tachyglossus aculeatus*) amongst pincushions of *Borya sphaerocephala* in Western Australia. Both the echidna and the borya are remarkable endemics of our region. *Borya* are resurrection plants, having leaves that can dehydrate completely during summer then rehydrate and green up after autumn rains. The biochemistry behind this ability has been put to use to create vaccines that remain active when dehydrated, rather than needing to be frozen.

CREDIT: FRED AND JEAN HORT

5 Strategic actions for taxonomy and biosystematics in Australia and New Zealand

THERE IS MUCH TO DO.

Australian and New Zealand taxonomists and biosystematists are world leaders, particularly in translating biodiversity research for public benefit.

Maintaining that world lead is important. Our region is megadiverse, but unusually for megadiverse regions Australia and New Zealand are also relatively wealthy nations. This brings responsibilities to our communities, our region, and the world. We have an unusually high number of evolutionarily old, rare and biologically significant lineages that provide important insights into the evolution of life on Earth. As island nations, Australia and New Zealand have much to gain from effectively securing our borders against biosecurity threats and for promptly and effectively dealing with emerging incursions. Because of the large number of species found nowhere else, we also need very strong conservation measures to ensure that our biodiversity remains for future generations. All these need taxonomic science that is relevant, innovative, and sustainably resourced.

Fronds of the remarkable kidney fern (*Hymenophyllum nephrophyllum*), a New Zealand endemic. The leaves curl up tightly when dry then unfurl after rain, leading to one of its Māori names, *kopakopa* (to wrap or clasp).
CREDIT: JOHN HUNT

However, there is still much to do. Many species remain to be discovered, named and documented. Many of these are rare and threatened. Others will have impacts, both positive and negative, for human health, food production and environmental sustainability. Still others may provide important economic benefits to industry, medicine and science. Biodiversity needs, impacts and risks cannot be managed, or benefits realised, when many species remain unrecognised.

With available and emerging technologies, and with sufficient investment, a step change is possible in the discovery, documentation, understanding, protection and utilisation of our natural assets.

We outline in this section how these step changes can be achieved, based on six key initiatives: accelerating discovery; enhancing services; engaging with Indigenous knowledge; improving our infrastructure; educating for the future; and supporting our sector. These key initiatives are supported by 22 strategic actions.

This consensus vision for transforming taxonomy and biosystematics in Australia and New Zealand has been developed through extensive consultation with the taxonomy and biosystematics community and its stakeholders. We are united in seeking to implement this plan.

5.1 Key initiative 1: Accelerating discovery

We will transform our understanding of Australian and New Zealand biodiversity by accelerating species discovery, classification, and exploration of its evolutionary history. This transformation will support new science and enable new and emerging tools for end users and stakeholders.

Species discovery and classification, and an understanding of the evolution of life on Earth, are the building blocks for understanding biodiversity and are core activities for taxonomy and biosystematics.

A significant acceleration is needed in these activities because current effort is not commensurate with current needs or opportunities. Human impacts on the planet, including species extinctions, are accelerating, as are threats to biodiversity, agriculture, and human and animal health from invasive organisms and environmental change. At the same time, opportunities to discover, document, conserve and utilise biodiversity are growing all the time. Implementation of this initiative will ensure that we meet these needs and opportunities.

> *"With new information technology and rapid genome mapping now available to us, the discovery of Earth's species can now be sped up exponentially. We can use satellite imagery, species distribution analysis and other novel tools to create a new understanding of what we must do to care for our planet. But there is another crucial aspect to this effort: It must be supported by more "boots on the ground," a renaissance of species discovery and taxonomy led by field biologists."*
>
> — *E.O. Wilson*. New York Times, 3 March 2018

The acceleration of effort, however, needs to be targeted well. Need is not evenly distributed amongst taxa: some taxonomic groups are more important for end users than others, and resolution of important scientific questions requires a better than *ad hoc* approach. The acceleration envisaged here will be strategic, focused and efficient. Focal taxonomic groups will be those most relevant for impact areas such as conservation, biosecurity and biological control, pest management, human and animal health, and biomimicry.

This initiative will be supported by three strategic actions.

Strategic action 1.1

We will significantly increase the rate at which new species in Australia and New Zealand are discovered, resolved, named and documented.

New species and other taxa are core data streams for biodiversity. At the current rate of discovery and naming of species, it will take several centuries to approach a complete documentation of Australia's and New Zealand's biodiversity, particularly in hyper-diverse groups such as fungi, many invertebrates and microbes. If the rate of extinction continues to be higher than the rate of discovery, many species will be extinct before they, and their roles and potentials, are known. Clearly, business-as-usual needs to change.

The step change that occurred in Australia in the mid-1970s following the establishment of the Australian Biological Resources Study shows that substantially increasing the rate of naming and documentation of our biodiversity is possible. With a combination of reinvestment in staffing, collections and capacity, new technologies, and enhanced capability to use these technologies, another similar increase is possible.

New technologies for this action include rapidly evolving genomic methods, new imaging and image analysis techniques, platforms to ensure that specimen data are born-digital rather than digitised, big-data analysis and machine learning, virtual taxonomy workbenches and rapid online publication. Where appropriate, these technologies should be deployed in specialist hubs, from where they can be made available to all taxonomists and biosystematists and other researchers. This initiative will place Australia and New Zealand as global leaders in tackling the documentation of biological megadiversity.

A target for this action will be to name all known, unnamed species in relatively well-documented groups, and at least half of the known, unnamed species in taxonomically hyperdiverse groups by 2028. Well-documented groups include plants and vertebrates; poorly documented groups include terrestrial and marine invertebrates, fungi and microbes. Known, unnamed species are those that have been informally recognised in biodiversity collections, but have not yet been taxonomically studied and named.

We will also build capacity and capabilities during this decade to drive an acceleration to hypertaxonomy—the comprehensive documentation of Australian and New Zealand species before mid-century. We are the only OECD countries in a megadiverse region; we should aim to be the first OECD countries to fully document our biodiversity.

Strategic action 1.2

We will expand opportunities for species discovery and biodiversity inventory in the field.

In Australia, this will be done by working with the Australian Biological Resources Study (ABRS) and other partners to support and expand the successful Bush Blitz and BioBlitz programs. In New Zealand we will work to establish a similar program, to target poorly known and otherwise strategically important areas, and to support the vouchering, collections management and taxonomy that arises from field work.

Strategic action 1.3

We will build a comprehensive framework to understand the evolution of the Australian and New Zealand biota.

Strategic DNA sequencing will allow us to build a well-resolved phylogeny—an evolutionary tree—of Australia's and New Zealand's biodiversity. We will aim for at least a tenfold increase in phylogenetic resolution compared with that achievable in 2018. This will be a key tool for utilising and conserving biodiversity, predicting and mitigating impacts of global change, and answering some of the most fundamental questions in biodiversity science.

The sea slug *Pearsonothuria graeffei* spawning on the Rowley Shoals off the coast of Western Australia.
CREDIT: JOHN HUISMAN

About strategic action 1.3

Phylogenies provide the overarching conceptual framework for biodiversity. All organisms have evolved from other organisms; a phylogeny shows the patterns of their evolution. Phylogenies in modern taxonomy and biosystematics guide the correct naming of organisms, their scientifically robust classification, and an understanding of their evolution and characteristics.

A phylogeny that covers the breadth of the biota will allow us to answer some of the biggest scientific questions concerning our biodiversity. Key amongst these are:

- How has the Australasian biota evolved before and after the breakup of Gondwana and Australia's approach to Asia?
- How have Australian and New Zealand organisms adapted to the significant changes that have occurred over that time, particularly in climate?
- What can we learn from their past about their capacity to adapt to current and future environmental change?
- And why are so many lineages in Australasia evolutionarily isolated, geographically restricted, and sister to lineages that have dominated the rest of the world?

As well as answering big scientific questions, a complete phylogeny will guide and support bioprospecting initiatives, help guide biosecurity and biocontrol programs, and provide critical infrastructure for emerging technologies and industries based on eDNA and metagenomics.

A 150 million year old Wollemia fossil from New South Wales, with a sprig from a living tree.
CREDIT: J. PLAZA / © ROYAL BOTANIC GARDENS SYDNEY & DOMAIN TRUST

5.2 Key initiative 2: Enhancing services for end users

We will integrate and synthesise knowledge of biodiversity in accessible resources for stakeholders, including government, industry and the community. Resources will include accessible, sophisticated, integrated, world-leading tools to accurately identify Australia's and New Zealand's organisms, and information portals to transform biodiversity decision-making and make biodiversity knowledge accessible for applications across conservation, health, biosecurity and food production.

Although named species and other taxa are a core framework for organising our knowledge of biodiversity, names alone provide little information or meaning for end users—they are the keys for accessing knowledge stored elsewhere. And it is this knowledge, about distribution, ecology, conservation status, morphology, ecological traits, biochemistry and metabolomics, that provides most value for decision-making and facilitates new industries.

Taxonomy and biosystematics have a long history of translating research into accessible forms for end users. New technologies, including in data management, integration, machine learning and mobile platforms, will substantially enhance these knowledge transfers.

This initiative will be supported by two strategic actions.

A velvet worm in the phylum Onychophora, Velvet worms are ancient, diverse, and taxonomically poorly known predators of insects and other arthropods in wet forests.
CREDIT: TAPIO LINDERHAUS

Strategic action 2.1

We will create a comprehensive, integrated, accessible service for identification of Australian and New Zealand organisms, based on DNA sequences, morphology, and images.

Rapid and accurate identification of organisms is a key need for our end users. Traditionally, identifications have been based on morphological identification keys, and these will remain important in an integrated identification system. The rapidly falling costs of DNA sequencing holds promise for a universal DNA-based identification service. Similarly, machine processing of digital images is leading to easy-to-use, image-based identification tools for some taxonomic groups. Currently, identification resources for organisms in Australia and New Zealand are widely dispersed, often inaccessible and not well integrated. There are currently no reliable, deployed systems to allow effective DNA-based or image-based identifications across most taxonomic groups.

Australia and New Zealand have led the world in biodiversity identification technology for a generation. This portal will be a world first, and will allow anyone to identify any specimen as accurately as possible.

This action will initially focus on strategically important groups, while building a framework for the identification of all Australian and New Zealand organisms.

Strategic action 2.2

We will provide authoritative online profiles for Australian and New Zealand species and other taxa, both living and extinct.

Australian and New Zealand taxonomists have a long history of delivering detailed information on species, to help end-users understand and manage our biodiversity. This action will extend the impact and reach of this work and harness new capabilities in information systems to deliver up-to-date, high-quality, authoritative information written for a variety of audiences, for all major groups of Australian and New Zealand organisms, to species level or a higher taxonomic rank as appropriate.

These profiles—online encyclopedias of living and extinct biodiversity—will be key resources and references for our end users, from schoolchildren to scientists and other professionals.

5.3 Key initiative 3: Engaging with Indigenous knowledge

We will engage with Indigenous groups and ensure that their perspectives, needs and aspirations are incorporated across the activities of this plan.

Indigenous knowledge of biodiversity in Australia and New Zealand results from a long history of utilisation, observation and experience. However, there is often a profound disconnect between Indigenous biodiversity knowledge systems and the taxonomy and biosystematics conducted in our institutions. Existing initiatives to bridge this gap include co-governance of some collections, close involvement of Indigenous communities in biodiversity surveys and in the resolution and naming of newly discovered taxa, and development of teaching resources that help reinforce the importance of Indigenous perspectives on biodiversity. This initiative seeks to build on and extend these successful examples of mutually beneficial engagement.

Strategic action 3.1

Guided by the principles of Te Tiriti o Waitāngi[42]—the Treaty of Waitangi—we will work with Māori to build respectful partnerships for the mutual exploration of biodiversity, including its significance and opportunities.

This engagement will lead to collaborations with mana whenua to generate taxonomic and biosystematics information that fulfils agreed aspirations; for example, knowledge for kaitiakitanga[43], and exploring ways in which mātauranga Māori[44] can inform taxonomy and biosystematics.

Strategic action 3.2

We will establish a national program in Australia to record Indigenous nomenclature for all groups of organisms in all major language groups.

This action will be planned and established with Aboriginal and Torres Strait Islander communities and their knowledge custodians in Australia, in culturally appropriate ways and with full respect for Indigenous knowledge traditions. Outcomes from this action will be crafted to ensure maximum benefit for communities.

An unidentified rainforest beetle. Beetles are the most diverse group of insects.
CREDIT: TAPIO LINDERHAUS

This giant robber fly (*Phellus piliferus*) has captured and killed a buprestid beetle (*Temognatha heros*). Both the beetle and fly are some of the largest in Australia—the beetle in this photograph is 55 mm long.
CREDIT: JIRI LOCHMAN

42 That is, partnerships, reciprocity, autonomy, active protection, options, mutual benefit, equity, equal treatment and redress.

43 Definition: stewardship, protection and legacy.

44 Definition: the body of knowledge originating from Māori ancestors, including the Māori world view and perspectives, Māori creativity and cultural practices.

5.4 Key initiative 4: Improving our infrastructure

We will manage and enhance the national biodiversity collections, their ancillary digital resources, and other key infrastructure and information in Australia and New Zealand to underpin evidence-based decision-making, scientific and industrial innovation, and world-leading research.

Well-managed biodiversity infrastructure, centred on well-curated collections, their associated databases, and other biodiversity information resources such as checklists and image banks, is key to delivering high-quality sciences, services, and this plan. Australia and New Zealand are currently world leaders in managing and deploying biodiversity information and in bioinformatics. With the challenges of managing rapidly increasing amounts of data, while maintaining a strong grounding of these data in voucher specimens, this leadership is in danger of being lost.

This initiative will be supported by eight strategic actions.

The type specimen of the *bryozoan Craspedozoum spicatum* (microslide, Registration no. F 45615-4).

CREDIT: JON AUGIER / MUSEUMS VICTORIA CC BY 4.0

Strategic action 4.1

We will enhance the integration, coordination and profile of the biodiversity collections in Australia and New Zealand.

Biodiversity collections in Australia and New Zealand comprise national science infrastructure and investment that is equivalent in dollar and scientific value to large telescopes, particle colliders and other high-end science infrastructure. The replacement value[45] of the Australian collection is approximately A$7 billion, and that of the New Zealand collection more than NZ$1 billion.

However, because the collections are widely dispersed and managed under a variety of jurisdictions, they are rarely regarded as an aggregate, integrated whole. This limits their visibility, which in turn at times leads to a lack of understanding of their strategic importance and value.

This action will result in enhanced profile, visibility, coordination and security for Australia's and New Zealand's biodiversity collections, and opportunities for coordinated, cross-institution funding. It will be established by working with and through existing peak bodies and government at all levels.

Strategic action 4.2

By 2028 we will have unified, authoritative checklists of all named species and other taxa in Australia and New Zealand, native and naturalised.

Ensuring that Australia and New Zealand maintain up-to-date checklists of species and other taxa is important to enable governments and other stakeholders to readily access the best available authoritative information on the taxa that occur in each jurisdiction, to support conservation legislation and actions, biosecurity and quarantine, compliance with international conventions, and to provide the essential taxonomic backbone for other information systems that manage biological information. This action will extend and enhance ongoing work by the taxonomy and biosystematics community in developing and maintaining the Australian National Species Lists (coordinated and managed by ABRS), and the New Zealand Organisms Register (coordinated and managed by Manaaki Whenua – Landcare Research).

45 Replacement value is the approximate cost of recollecting specimens to replace ones lost through disaster or misadventure. Note that many specimens in the collections, particularly historical ones that represent extinct species or populations, are literally irreplaceable. The scientific value of biodiversity collections is substantially higher than the dollar replacement value.

Strategic action 4.3

We will build a curated, vouchered reference library of DNA sequences covering the breadth of the tree of life in our region.

The reference library will be built in collaboration with national and international initiatives such as GenBank and Bioplatforms Australia (a national research capability supported by the National Collaborative Research Infrastructure Strategy). It will include rigorously curated DNA sequences covering all taxonomic groups (to an appropriate taxonomic depth), including both native and invasive taxa. This is likely to be the world's first such DNA library for any megadiverse country and any continent, and will provide a key framework for managing, researching and documenting our biodiversity, for discovering new species using emerging technologies such as metagenomics and eDNA approaches, and for DNA-based identification tools for many purposes including biosecurity.

Strategic action 4.4

We will establish a freely accessible, authoritative, curated online image bank of the best available diagnostic images of Australian and New Zealand organisms.

Images are an important resource for identification, diagnosis and confirmation of identifications provided by other means. For maximum effectiveness, rigorous quality control of images, including vouchering, identification by experts, and standardisation, is important. As with the other identification services, this will initially focus on strategically important groups.

Strategic action 4.5

We will create and maintain a database on primary type specimens of Australian and New Zealand species, and provide high-quality digital images of all such specimens held in Australia and New Zealand.

Type specimens are the key specimens that anchor the application of names to taxa; they are thus particularly important for researchers when trying to determine whether a taxon is new or already named. Providing information about, and digital access to, type specimens reduces risk to our collections, and will enhance researchers' abilities to conduct taxonomic research.

Strategic action 4.6

By 2028 we will build a curated and well-managed trait library capable of capturing key ecological and morphological traits.

Taxonomic and biosystematic research generates a wealth of morphological, anatomical, ecological, genetic, and other data. Capturing these in a well-structured trait library will provide an ever-growing resource to answer questions in a wide range of fields, provide information needed by stakeholders, and support online identification.

Strategic action 4.7

By 2028 we will have databased all botanical specimens, and at least half of all zoological specimens in Australian and New Zealand biodiversity collections.

This will substantially improve our understanding of the distribution, status and management needs of all known taxa in Australia and New Zealand, including rare and threatened native species and economically and environmentally significant pests. It will also provide more effective and wide-reaching access to critical information that is currently inaccessible in many collections.

Strategic action 4.8

By 2028 all digital objects, datasets and taxonomic resources associated with biodiversity collections will have at-source, citeable, discoverable, resolvable, universally unique identifiers.

Universally unique digital identifiers are critical to allow digital objects (such as specimen records, images, names etc.) to be attributed, exchanged, explored and analysed in ways not previously possible or considered. This is particularly important because some of the core units of analysis (species and other taxa) may change over time with the growth of taxonomic knowledge. Universally unique identifiers will allow these changes, and the relationships between objects such as names and specimens, to be tracked. This in turn will allow better, more accurate taxonomic and related science.

Jewel beetles *Stigmodera gratiosa* feeding and mating on the featherflower *Verticordia huegelii*.
CREDIT: FRED AND JEAN HORT

5.5 Key initiative 5: Educating for the future

We will inspire the public and the next generation of workers and leaders in our field to celebrate the unique value and immense potential of the Australasian biota. We will do this through education at all levels, including primary to tertiary, up-skilling biodiversity professionals throughout their careers, and beyond formal education to lifelong learning and community participation in research.

Education is key to the future of taxonomy and biosystematics, and ultimately to conservation, sustainable use of biodiversity, and rich cultural relationships with the living world. We need to inspire the public about the richness of our biodiversity and natural assets; we need to educate our children and our communities to appreciate and understand biodiversity and its importance for their lives; and we need to train the next generation of leaders and other workers in the field.

This initiative will be supported by three strategic actions.

A cicada infected by a fungus in the genus *Metarhizium*. This taxonomically challenging genus includes species that are useful for biological control of insect pests.
CREDIT: TAPIO LINDERHAUS

Strategic action 5.1

We will contribute to the development of integrated teaching resources to assist in and support the teaching of biodiversity and the fundamentals of taxonomy and biosystematics, from primary schools to postgraduate studies.

Currently, national teaching resources, particularly at tertiary level, are scattered and uncoordinated, and are available to only a minority of students in Australia and New Zealand. By coordinating effort and developing shared online content, short courses and units, we will ensure that training opportunities are as widely available as possible for the greatest possible number of students.

We will work with the school education programs of the Australian Academy of Science to develop these resources, which will be aligned with the national STEM curricula at primary and secondary levels, and with university and TAFE-level teaching of biological diversity, evolution and modern methods in taxonomy and biosystematics.

Strategic action 5.2

Working with industry peak bodies, we will develop a targeted package of short courses in identification and taxonomy of key groups of organisms.

These will support an accreditation system and in-service training for biodiversity industry professionals, taxon-specific training for postgraduate students, and lifelong learning in the community.

Strategic action 5.3

We will work to support and enhance community and citizen science participation in taxonomy and biosystematics.

Community participation in taxonomy and biosystematics is an important way to build support for the sector and enhance community engagement with biodiversity. Many existing citizen science projects use the taxonomic framework and knowledge provided by taxonomists and biosystematists, and these will continue to be supported and enhanced by actions in this plan. There is scope also for initiating new citizen science programs that are more closely linked to, and directly engage with, the core business of taxonomy and biosystematics.

5.6 Key initiative 6: Supporting our sector

We will support strategic growth of the taxonomy and biosystematics sectors in Australia and New Zealand, and ensure that taxonomic expertise is available where and when it is required by our nations, with clear career paths, long-term sustainability, and a focus on building and maintaining critical expertise.

The vision outlined in this plan can be realised only if the taxonomy and biosystematics workforce is strategically enhanced and supported. Employment in the taxonomy and biosystematics sector has declined or flat-lined for 30 years, at a time when the needs of end users for good taxonomy and biosystematics is growing rapidly. Many taxonomists are hired in positions that do not explicitly support taxonomic and systematic research, leading to under-utilisation of their expertise. The workforce is ageing, and career opportunities for new entrants are few.

Like many other cutting-edge sciences, taxonomy and biosystematics are becoming increasingly data-rich, and management and analysis of big data are becoming increasingly important. However, staff employed to manage biodiversity data are too few, and are usually viewed as technical officers, with limited pay and career opportunities to match. Enhancing the capabilities of this sector of the workforce will be particularly important to realising the vision of this plan.

This initiative will be supported by four strategic actions.

Strategic action 6.1

We will engage with organisations to improve succession planning, mentoring and enhanced capabilities for the taxonomy and biosystematics sector in Australia and New Zealand.

This will be done by identifying strategically important capabilities that must be retained or enhanced, and key taxonomic groups for which in-country expertise is lacking. Mentoring under this strategy will include both down-mentoring (experienced practitioners mentoring early-career researchers to pass on key knowledge) and up-mentoring (early-career researchers mentoring experienced practitioners in new techniques and methods).

Strategic action 6.2

We will create a workplace culture where employed taxonomists and biosystematists spend on average more than 50 per cent of their work hours engaged in taxonomic and biosystematic research.

Surveys show that the amount of time spent doing the core business of taxonomic and biosystematics research has been declining over recent decades. While other activities of these research positions are important, reversing this decline will be beneficial both for the workforce and for productivity in the sector. Similarly, reducing the amount of time spent by highly skilled taxonomists on repetitive tasks such as simple species identifications, by deploying automated methods for routine tasks, will allow a better deployment of skills.

Strategic action 6.3

By 2028, we will achieve gender equality and diversity in new appointments in the taxonomy and biosystematics workforce.

Although the taxonomy and biosystematics community does not have a major gender imbalance, more work is needed in this area to achieve full gender equity in numbers, work conditions and career prospects, and gender equality in leadership roles. Diversity in appointments is also an issue, with too few appointments from Māori, Indigenous, other ethnic, and other non-mainstream backgrounds.

Strategic action 6.4

Working with existing peak bodies, sector organisations and stakeholders, we will establish independent, resourced, professional bodies in Australia and New Zealand to represent and promote the taxonomy and biosystematics sectors.

The professional bodies will provide high-level leadership, coordination, strategic planning, science communication, advocacy to government at all levels, and enhanced linkages to end users and stakeholders. They will be responsible for coordinating the implementation of this decadal plan. In Australia, a new body to be called Taxonomy Australia will be established. In New Zealand this action will be undertaken by the existing National Systematics and Taxonomic Collections Working Group, with consideration given to securing ongoing funding to support a secretariat for this group.

A male freshwater amphipod crustacean, possibly *Allorchestes compressa*. Amphipods are ecologically important but poorly known; this species may comprise several closely related species, the distributions of which are poorly understood.

CREDIT: MICHAEL MARMACH / MUSEUMS VICTORIA CC BY 4.0

A female giant prickly stick insect (*Extatosoma tiaratum*).
CREDIT: TAPIO LINDERHAUS

6 Implementing this plan

THE TAXONOMY AND BIOSYSTEMATICS COMMUNITY IN AUSTRALIA AND NEW ZEALAND HAS ENDORSED THIS PLAN, AND COMMITS TO ITS IMPLEMENTATION TO THE GREATEST EXTENT POSSIBLE, GIVEN APPROPRIATE INVESTMENT, RESOURCING AND CAPACITY-BUILDING.

This decadal plan is ambitious in scope. It seeks to bring about a substantial change in the taxonomy and biosystematics sector in Australia and New Zealand. In particular, it seeks to substantially accelerate the rate at which the taxonomy and biosystematics community is able to document the biota of Australia and New Zealand, to make that rate commensurate with need, and to dramatically improve the services provided to end users.

Three necessary preconditions for the vision of this plan to become a reality are:

1. the development and execution of strategic, targeted and detailed implementation plans to underpin each of the keystone initiatives of this plan,
2. close integration, communication and formal partnerships both within the sector and with stakeholders and end users, to ensure that implementation is effective and focused on outcomes, and
3. adequate capacity in the taxonomy and biosystematics community.

Resourcing for taxonomy and biosystematics in Australia and New Zealand is complex, involving two national governments, all Australian state and territory governments, Australia's CSIRO, New Zealand's Crown Research Institutes, national and regional museums, and universities in both countries.

For this reason, this plan does not include specific funding objectives, and there is no dollar value to the plan or its key actions. Rather, the plan establishes a vision and framework for negotiations and proposals across government and to the private sector, to be developed as part of the implementation process.

Two key funding priorities that cross-cut many activities in the plan are substantial reinvestment by the Australian Commonwealth Government in the Australian Biological Resources Study (ABRS), and the establishment in New Zealand of an ABRS-equivalent. ABRS has been a key driver for taxonomy and biosystematics research in Australia, and its establishment in 1973 contributed to a demonstrable step-change in the rate at which new knowledge of Australian biodiversity was created, accrued and disseminated to end users. Given that a key vision for this plan is to create the conditions for another such step change, it is reasonable to expect that ABRS will continue to play a key role, and it should be supported, enhanced and expanded.

A boab (*Adansonia gregorii*) in Western Australia's Kimberley. All other species of boab occur in East Africa and Madagascar; why one species occurs in Australia is a biogeographic mystery.
CREDIT: JANE MELVILLE

In New Zealand, taxonomy and biosystematics have been declining for two generations since the end of the second world war, the result of protracted and progressive declines in funding. The Australian ABRS model is a proven one, and we recommend that the establishment of a New Zealand equivalent be considered as a matter of priority.

Most recurrent funding for taxonomic institutions is non-discretionary—salaries and maintenance costs for the collections, buildings and equipment. Funding for research is modest at best. A richer layering of funding, including reinvestment in research, is necessary if the vision of this plan is to be achieved.

Investments in taxonomy and biosystematics should be broadly based and not entirely focused on government appropriations for collections institutions or modest taxonomic research programs. There is considerable scope for private-sector investment in taxonomy and biosystematics.

The framework science provided by taxonomy and biosystematics is too often regarded as a free service: many businesses, industries, and government agencies that do not fund taxonomy and biosystematics are beneficiaries of, and capitalise on, its work. The past decade has seen a trend towards drawing down on taxonomic and biosystematic capital (the knowledge generated in previous decades) rather than building new capital. Our vision for the next decade is to create substantial new taxonomic capital in the form of new taxa and new knowledge.

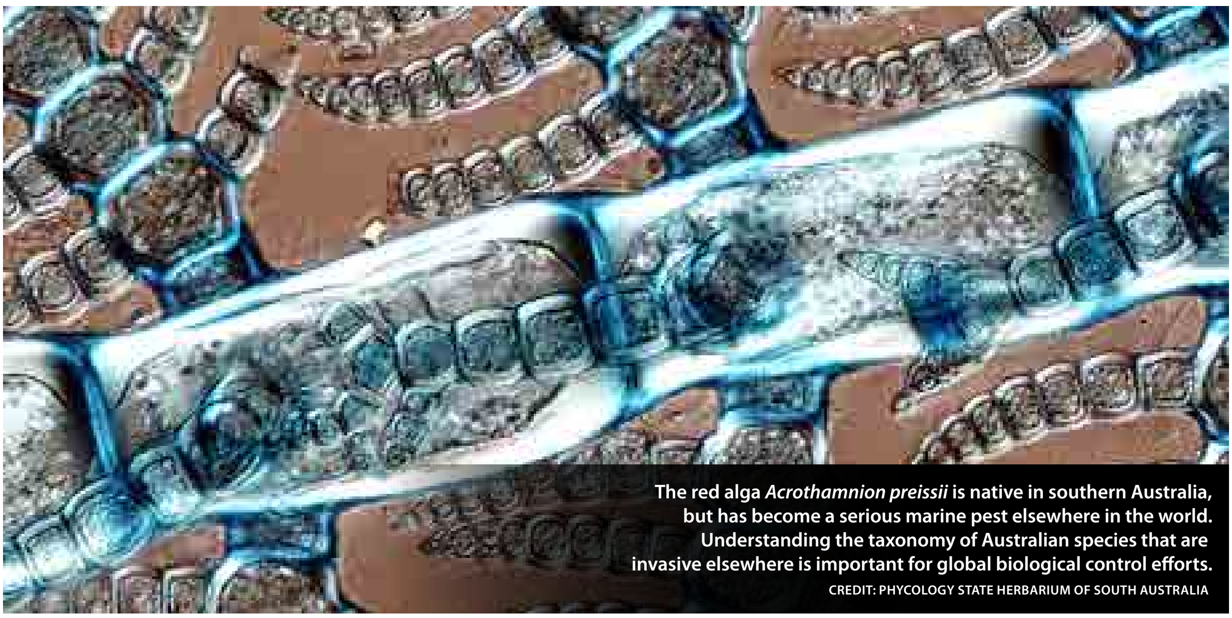
This will require significant investment. With the new opportunities and revolutionary new technologies available to the discipline, this investment will bring very high returns.

Although integration and coordination of taxonomy and biosystematics in Australia and New Zealand have been high compared with global averages, the challenges and opportunities of the next decade require a step change in this as well.

For this reason, a second key recommendation of this plan is the establishment of Taxonomy Australia, and continuing support for its equivalent, the National Systematics and Taxonomic Collections Working Group, in New Zealand. These will have responsibility for, and carriage of, this plan, including its advocacy, development of the necessary underpinning implementation plans, development of resourcing proposals, and coordination of enhanced engagement within and beyond the sector. Such bodies have proven successful and effective in other sectors of science. The taxonomy and biosystematics communities in both countries will investigate governance models and establish these bodies as a priority.

Implementation of this plan will be a complex undertaking, with many moving parts and partners. A key role for Taxonomy Australia and its New Zealand sister body will be to review implementation in five years' time (2023), to assess lessons learnt, and to amend or add strategic actions as necessary.

The taxonomy and biosystematics community in Australia and New Zealand has endorsed this plan, and commits to its implementation to the greatest extent possible, given appropriate investment, resourcing and capacity-building.



The red alga *Acrothamnion preissii* is native in southern Australia, but has become a serious marine pest elsewhere in the world. Understanding the taxonomy of Australian species that are invasive elsewhere is important for global biological control efforts.
CREDIT: PHYCOLOGY STATE HERBARIUM OF SOUTH AUSTRALIA

The endemic New Zealand tui (*Prosthemadera novaeseelandiae*) feeding on New Zealand flax (*Phormium tenax*). New Zealand has relatively few native terrestrial vertebrates such as birds, reptiles and frogs, but many of them are remarkable and evolutionarily important.
CREDIT: JOHN HUNT

Partners and process

The taxonomy and biosystematics communities in Australia and New Zealand and key stakeholders have worked collaboratively to develop this decadal plan, and its recommendations comprise a community consensus.

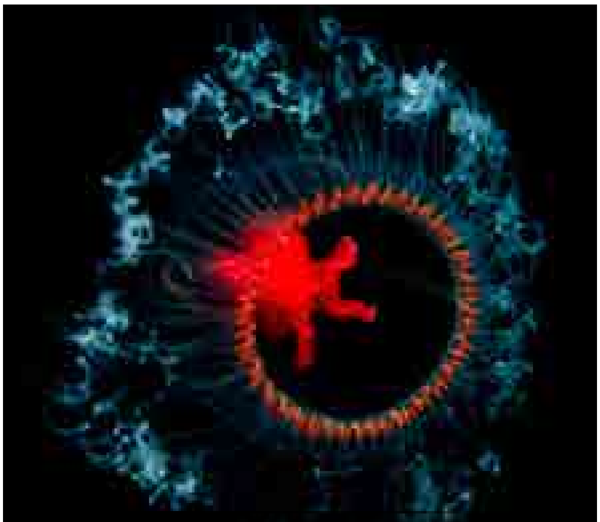
Development was coordinated by the Australian Academy of Science, the Royal Society Te Apārangi, the Council of Heads of Australasian Herbaria (CHAH), the Council of Heads of Australian Faunal Collections (CHAFC), the Australasian Systematic Botany Society (ASBS), and the Society of Australian Systematic Biologists (SASB). It was funded by the Ian Potter Foundation and other partners listed in Acknowledgements.

Extensive consultations were conducted both within the taxonomy and biosystematics communities, and with a wide range of stakeholders. These included:

- presentations and discussion forums at sector meetings, conferences and symposia
- an intensive 'town hall' style workshop for sector and stakeholder participants in each capital city in Australia and in the three major cities in New Zealand
- individual meetings with leaders in the field and with significant stakeholders
- discussions, commentary and feedback through social media platforms and a dedicated community blog site.

Over 400 participants took part in the forums or were directly consulted.

Substantial and detailed conversations and feedback during the development of this plan were provided by the project's Working Group and Steering Committee (members of whom are listed in Appendix 1) and the National Systematics and Taxonomic Collections Working Group in New Zealand.



The medusa stage of *Turritopsis rubra*. *Turritopsis* jellyfish are of great scientific interest, as some species may be effectively immortal.
CREDIT: RICHARD ROBINSON

The remarkable flowers of the Australian snake gourd *Trichosanthes cucumerina*.
CREDIT: BERNARD DUPONT / FLICKR CC BY-SA 2.0

Endorsements

This decadal plan is endorsed and supported by the following organisations:

- The Australian Academy of Science
- The Royal Society Te Apārangi
- The National Systematic and Taxonomic Collections Working Group (NZ)
- The Australasian Systematic Botany Society
- The Society of Australian Systematic Biologists
- The Council of Heads of Australasian Herbaria
- The Council of Heads of Australian Faunal Collections
- The Atlas of Living Australia

A Western Australian featherflower, *Verticordia ovalifolia*.
CREDIT: KEVIN THIELE

False clownfish (*Amphiprion ocellaris*) in their host anemone, a magnificent sea anemone (*Heteractis magnifica*). The popular genus *Amphiprion*, which includes the clown- and anemonefishes, is taxonomically and evolutionarily complex; recent molecular studies have shown that similar-looking species are not always closely related. The clownfish will remain with their host for their entire lives.
CREDIT: JOHN HUISMAN

Appendix 1
Members of the Advisory Committee and Working Group

Project lead

Dr Kevin Thiele	Australian Academy of Science

Advisory committee

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Professor Pauline Ladiges AO FAA	Professorial Fellow, Botany, The University of Melbourne
Professor Craig Moritz FAA	Director, Centre for Biodiversity Analysis, Australian National University
Professor Wendy Nelson MNZM FRSNZ	Principal Scientist, National Institute of Water and Atmospheric Research; School of Biological Sciences, University of Auckland
Dr Thomas Trnski	Head of Natural Sciences, Auckland War Memorial Museum

Working group

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Professor David Cantrill	Executive Director Science, Royal Botanic Gardens Victoria
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Ms Ailsa Holland	Science Leader, Queensland Herbarium
Dr John Hooper	Head of Biodiversity and Geosciences Program, Queensland Museum
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Dr Peter Johnston	Manaaki Whenua – Landcare Research
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Dr Zoe Knapp	Australian Biological Resources Study, Department of the Environment and Energy
Dr John La Salle	Director, Atlas of Living Australia
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Dr Rolf Schmidt	Collection Manager, Invertebrate Palaeontology, Museums Victoria
Professor Roger Shivas	Curator, Queensland Plant Pathology Herbarium
Dr Jen Tate	Senior Lecturer in Plant Systematics, Curator Dame Ella Campbell Herbarium, Massey University
Dr Ken Walker	Senior Curator, Museums Victoria
Dr Genefor Walker Smith	Collection Manager, Marine Invertebrates, Museums Victoria
Professor Michelle Waycott	Chief Botanist, State Herbarium of South Australia
Dr Peter Weston	Honorary Research Associate, Systematic Botany, National Herbarium of New South Wales
Mr Anthony Whalen	General Manager, Australian Biological Resources Study, Department of the Environment and Energy
Dr Nerida Wilson	Manager and Senior Research Scientist, Molecular Systematics Unit, Western Australian Museum
Dr Aaron Wilton	Portfolio Leader – Characterising Land Biota and Director of the Allan Herbarium, Manaaki Whenua – Landcare Research
Professor David Yeates	Director, Australian National Insect Collection, CSIRO

Fruiting sporophylls of the rare tropical cycad *Cycas platyphylla*. Cycads are an ancient group that were dominant during the age of dinosaurs. Many species are rare and threatened. Understanding cycad taxonomy is important for regulating international trade in endangered species.
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