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Status of Australia’s Forest Genetic Resources 2021

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Acronyms

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ALA	Atlas of Living Australia
ASBP	Australian Seed Bank Partnership
ATSC	Australian Tree Seed Centre
CSIRO	Commonwealth Scientific Industrial Research Organisation
DAWE	Australian Government Department of Agriculture, Water and the Environment
EPBC Act	Commonwealth Government *Environment Protection and Biodiversity Act 1999*
FAO	Food and Agriculture Organization of the United Nations
FGR	Forest Genetic Resources
NFPS	*National Forest Policy Statement 1992 (1995)*
PIRSA	Primary Industries and Regions South Australia
QDAF	Queensland Department of Agriculture and Fisheries
RIRDC	Rural Industries Research and Development Corporation
SPA	Seed Production Area
TBA	Tree Breeding Australia

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Executive summary

Rationale and context

Forest genetic resources underpin the diversity of Australia's forests and forest species as well as their productive capacity. Continual improvement in the understanding of Australia's forest genetic resources allows better conservation management of forests and forest species, and better management and development of forest resources for productive use. This report compiles the current status of Australia's forest genetic resources, and covers both native forest genetic diversity and management, and plantation tree genetics and improvement.

The report was prepared as Australia's Country Report for *The Second Report on the State of the World's Forest Genetic Resources,* a global assessment of forest genetic resources by the Food and Agriculture Organization of the United Nations (FAO), and uses the FAO definition of forest genetic resources as the genetic diversity within and among tree and other woody plant species. It serves as a source document for all users and stakeholders seeking information on current knowledge and research on Australia's forest genetic resources.

Australia has 132 million hectares of native forest and 1.8 million hectares of plantation forests. Together these play an important role in the country's economy, and provide essential ecosystem services such as biodiversity, clean water, and carbon storage. Australia's forests also supply a variety of wood and non-wood products including sawn timber, pulp logs for fibre, firewood, food, oils, fodder and Indigenous traditional uses. Several Australian species are also important internationally for wood, shelter for stock, tannin, firewood and soil conservation.

Australia has approximately 2,500 native tree species, the main genera being wattles (the genus *Acacia*, with almost 1,000 species) and eucalypts (the genera *Eucalyptus*, *Corymbia* and *Angophora*, with approximately 800 species). A total of 129 forest tree species and hybrids are listed by the FAO as forest genetic resources for Australia, including 115 native species and hybrids. These include species used for wood products, as well as species used for food, oil and fodder; this list includes some iconic and some threatened Australian forest species.

Just over half of the area of Australia's commercial plantation forests consists of exotic (non-native) softwood species such as *Pinus radiata*, *P. caribaea* and hybrids, while most of the remainder is native hardwood species such as *Eucalyptus globulus*, *E. nitens* and *E. grandis* as well as the native softwood species *Araucaria cunninghamii*. Australia's commercial softwood plantations are mostly managed on long rotations for sawn timber, while the commercial hardwood plantations are mostly managed on short rotations for pulpwood.

Native tea tree (*Melaleuca*) and macadamia (*Macadamia*) species are also grown in plantations, for production of oil and nuts respectively. There are also small-scale commercial plantings of other forest species for food products and other uses.

Forest genetic resource conservation and management

Australia's management and conservation of forests is underpinned by the *National Forest Policy Statement* (NFPS), which was jointly developed by the Australian, state and territory governments. The NFPS commits these governments to maintain an extensive and permanent native forest estate, and to manage the native forest estate in an ecologically sustainable manner for current and future generations, including conserving biological diversity (which includes genetic diversity), heritage, Indigenous and other cultural values.

Australia relies on in situ conservation as the main mechanism for conservation of forest genetic resources, but also has ex situ programs for a range of forest tree and other plant species.

In situ conservation extends across a number of mechanisms: the National Reserve System (NRS) (Australia's formal network of protected areas); the Comprehensive, Adequate and Representative system developed under Regional Forest Agreements; long-term management plans for the conservation and use of Australia’s native forests in multiple-use forests, including forests used for timber production; and voluntary formal conservation agreements on private land. When this range of mechanisms available for protection of biodiversity are considered together, as at June 2016 a total of 46.0 million hectares (35%) of Australia’s native forest was managed for the protection of biodiversity through formal and informal processes.

All the 115 native species and hybrids on the FAO list of forest genetic resources for Australia have populations conserved in situ in formal and informal reserves and protected areas; some of these species are also formally protected under legislation. Australia’s national, state and territory governments have regulations to limit and control the removal of plant and animal products from public and private forests. Management of production forests is regulated under state and territory legislation, with ecologically sustainable forest management an explicit goal, including the conservation and use of forest genetic resources.

Australia’s programs for ex situ conservation of forest species include seed banks, living collections, conservation stands, and seed orchards. Seed banks hold seed for 127 of the 129 species and hybrids listed by FAO as forest genetic resources for Australia. The Australian Tree Seed Centre is a major seed bank based at the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and a key supplier of seed for forestry species. Seed is also supplied from commercial seed orchards and some conservation plantings that have been converted to seed stands. A range of other seedbanks, including through the Australian Seed Bank Partnership, provide seed for conservation, research and revegetation projects.

Genetic diversity and tree breeding

A range of Australian organisations have conducted research over several decades to characterise the genetic diversity of Australian plant species, including CSIRO, universities, and government forestry and conservation departments. Most Australian genetic diversity work has been done on forestry species or threatened species.

Range size and disjunction, growth form, abundance and biome have the greatest effect on plant species genetic diversity in Australia. Currently, knowledge from non-molecular characterisation of within-species diversity (including from provenance and other trials) is not formally inventoried at a national or sub-national level. However, molecular and genomic data are now being captured by various national projects and databases.

The genetic resources of Australia's forests play a critical role in maintaining and developing plantation productivity. Attributes used for selection in tree breeding programs include faster growth, improved wood quality, pest resistance, and adaptability to different environments. Ongoing access to forest genetic resources will allow selection and development of tree crops more suited to the warmer and drier conditions predicted for southern and eastern Australia under climate change, or to the warmer and wetter conditions predicted for northern Australia.

Molecular technologies, and marker-assisted selection, are increasingly used in Australia and overseas to characterise species and assist breeding programs. Genomic sequencing of flooded gum (*Eucalyptus grandis*), a key plantation eucalypt species, is expected to accelerate eucalypt selection and breeding for productivity and wood quality. More than 200 Australian forest species have been examined for population genetic variation using molecular techniques, including 76 of the species listed by FAO as forest genetic resources for Australia.

Information on species genetic diversity is also being used to inform species management, conservation policy, and conservation activities.

Threats to forest genetic resources

There are at least 16,836 native vascular flora species (plants) in Australia's forests. Of these, 1,074 were listed as threatened species under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) as at 2016. Seventeen of the species on the FAO list of forest genetic resources for Australia are listed as threatened under the EPBC Act. Australia's main plantation species, and the majority of other tree species of economic and social importance, are not listed as threatened species. State and territory legislation also protects threatened species within jurisdictions.

Habitat fragmentation, reduction in population sizes, and spatial isolation of populations are threats that can reduce genetic variation within populations, and increase genetic divergence between populations, due to effects on gene flow and breeding. Changes in genetic diversity and breeding systems associated with these factors have been shown for several forest species. Australia's management responses to these threats include storage (banking) of genetic material as seed, restoring connectivity between populations, and assisted translocation.

Gene flow from plantations can alter the genetic make-up of local populations of native trees through introgression, and the potential for this has been documented for several eucalypt species and for macadamia. Australian jurisdictions have guidelines to manage gene flow through careful location and management of plantations, and assist conservation of adjacent wild genetic stock.

Climate change effects on Australian forest species include increasing temperatures, changing rainfall patterns, increased frequency of drought, and increasing fire frequency and intensity. Research to date has concluded that widespread eucalypts are likely to respond flexibly to a changing climate, and that revegetation using seed sources that match the projected future climate may confer even greater climate resilience. However, populations of many species with restricted ranges may be reduced or further restricted by climate change.

International contributions

Australia is a party to international agreements, treaties and conventions that are directly or indirectly relevant to the conservation, sustainable use and development of forest genetic resources. These include the Convention on Biological Diversity, the International Tropical Timber Agreement, and the World Trade Organisation Agreement on the Application of Sanitary and Phytosanitary Measures. Australia has signed, but not yet ratified, the Nagoya Protocol on Access and Benefit Sharing. Australia also participates in bilateral, multilateral, sub-regional and regional activities that are directly or indirectly related to forest genetic resources.

This report is available on the Forests Australia website at [doi.org/10.25814/6jxv-qs54](doi.org/10.25814/6jxv-qs54), together with other ABARES publications on forests, including *Australia's State of the Forests Report 2018* and associated data tables, figures, and maps.

1 Value and importance of forest genetic resources

1.1 Key points

- Forests are an important part of Australia's unique environment, and Australia's economy. In total, Australia has 134 million hectares of forest, including 132 million hectares of native forest, and 1.8 million hectares of plantation forest containing native and exotic species.
- Australia's forests are used for wood and non-wood products, tourism, education and recreation. Australia's forests also provide a range of ecosystem services, including maintenance of biodiversity, soil conservation and carbon storage. Many forested catchments also produce reliable supplies of high-quality water for rural and urban use.
- Australia's forest genetic resources underpin a range of economic, environmental, scientific and societal activities, from management of threatened species to development and use of forest products. Australia's forest genetic resources have also underpinned commercial plantation forestry in many areas overseas.
    - Australia has 1.8 million hectares of commercial forest plantations. This area comprises 0.7 million hectares of hardwood plantations, mostly of eucalypts, and 1.0 million hectares of softwood plantations, mostly of exotic pine species.
    - Australia's forestry and forest product manufacturing industries generated sales and service income of $A24.8 billion in 2018-19, and in 2016 directly employed 51,983 people.
    - A small number of forest species are grown commercially for food or medicinal properties, including macadamia and tea tree.
    - A total of 129 forest tree and woody shrub species and hybrids are listed by the FAO as forest genetic resources for Australia.
- Forests have cultural significance to Indigenous (Aboriginal and Torres Strait Islander) and non-Indigenous Australians. Extensive areas of forest are managed or co-managed by Indigenous traditional owners within the National Reserve System and on Indigenous-owned lands. Many forest species are used traditionally by Indigenous peoples.
- Tourism is an important part of the economy, contributing 2.5% to Australia's GDP in 2019-2020, including tourism and recreation in Australia's forested World Heritage sites, forested national parks, and other forested areas.
- Australia has strategies to enhance the contribution, value and importance of its forest resources, and to manage them sustainably.

1.2 Forest genetic resources

Genetic resources comprise the genetic diversity between and within species. More specifically, forest genetic resources are defined as the "heritable materials maintained within and among tree and other woody plant species that are of actual or potential economic, environmental, scientific or societal value" (FAO 2014a).

Trees and other woody plants are an essential part of forest ecosystems. They provide wood and non-wood forest products, maintain ecosystem services, fulfil environmental functions, and contribute towards sustainable development. Forest genetic resources have been used by humans for thousands of years to sustain life, and for centuries for improved food production, medicines and scientific knowledge (Department of the Environment and Heritage, undated). As part of this, the genetic diversity within species has been used to select qualities particularly desired by humans. The degree of genetic variability within species also determines their ability to adapt to environmental changes (FAO 2014a), whether those occurring between seasons or years, or those occurring due to longer-term processes such as climate change.

This report covers forest genetic resources within natural and planted forests; it also includes some comments on resources in other wooded lands (ecosystems with trees but with canopy cover less than 20%, sometimes called sparse woodland: FAO 2019). Where possible, information is provided about species currently listed by FAO as forest genetic resources for Australia (see **Appendix A** and **Appendix B**); other forest species are mentioned as relevant.

1.3 Values of forest genetic resources in Australia

Forests are an important part of Australia's unique environment, and Australia's economy. Australia's 134 million hectares of forest provide a range of wood and non-wood products that are used by Australians every day. Forests are also key in the provision of ecosystem services, providing habitat for biodiversity, clean water and carbon stores. Forests also provide opportunities for recreation, tourism and employment and for scientific and educational pursuits, and support cultural, heritage and aesthetic values, including being of great cultural value to Indigenous (Aboriginal and Torres Strait Islander) communities[1]. Trees and other woody plants provide the structure of forests, and their constituent genetic resources provide for the diversity of forest values.

1.3.1 Commercial forestry sector

Australia's commercial forestry sector is based on both plantations and native forests. The genetic resources in Australia's eucalypts and acacias underpin commercial plantation forestry in Australia, and also in many countries overseas.

Australia has 132 million hectares of native forest, of which 28.1 million hectares is available and suitable for commercial wood production (MIG and NFISC 2018), although only a proportion of this area is actually managed for wood production or will ever be harvested. Australia also has 1.8 million hectares of commercial plantations, comprising 0.7 million hectares of hardwood plantations, mostly of eucalypts, and 1.0 million hectares of softwood plantations, mostly of exotic pine species (Legg et al. 2021). Commercial plantations are mostly managed on long rotations for sawn timber, or on short rotations for pulpwood.

A total of 32.6 million cubic metres of hardwood and softwood logs was harvested in Australia in 2018–19, representing an increase of 26% over the previous decade (ABARES 2020b). Within this, the 2018–19 plantation log harvest was 28.6 million cubic metres, representing a 60% increase over the previous decade. Softwood logs accounted for 53% of the total harvest log volume in 2018-19, and hardwood logs accounted for 47%. With the exception of the small volume of cypress pine logs harvested from native forests, softwood logs originate in plantations. Hardwood logs originate in both native forests and plantations.

[1] Aboriginal and Torres Strait Islander peoples and communities are collectively called Indigenous peoples and communities in this report.

Data from the Australian Bureau of Statistics (ABS 2020) indicates that the gross value (at the mill door) of logs harvested in Australia in 2019–20 was $2.4 billion. Softwood logs provided 56% of this total value, and hardwood logs provided 44%. The value of Australian wood product exports in 2019-20 was $3.3 billion; of this, woodchip exports were the largest component (37%), followed by paper and paperboard exports (27%) and roundwood exports (18%).

The total value added by the forestry sector (the combined value added by the forestry and logging industry, and the wood and paper products manufacturing industry) was $9.7 billion in 2018–19, representing 0.5% of national gross domestic production. The wood and paper products manufacturing industry represented 82% of the total value added by the sector. In 2018–19, the forestry and forest product manufacturing industries generated sales and service income of $24.8 billion, representing 6.1% of Australia's total manufacturing sector (ABS 2020).

According to the 2016 census undertaken by the Australian Bureau of Statistics, total national direct employment in the forest sector in 2016 was 51,983 persons (MIG and NFISC 2018). In 2016, the forest and wood products industries directly employed 1,099 Indigenous people.

1.3.2 Other economic, social and cultural values

Other economic, social and cultural values of forest genetic resources include non-wood products and associated contributions to employment. However, the value of non-wood forest products is more difficult to estimate than the value of wood products from forests, due to a lack of national data. Some important commercial products are honey, wildflowers, seeds, and oils from eucalypts (species of *Eucalyptus*, *Corymbia* and *Angophora*), tea tree (*Melaleuca alternifolia*) and sandalwood (*Santalum)* (MIG and NFISC 2018).

Originally harvested from native forest, tea tree is now grown in plantations, and the oil produced is sold domestically and internationally. The total tea tree plantation estate is 4,500 hectares (Shepherd and Mieog 2019), with the majority on the north coast of New South Wales. The tea tree industry contributes $42 million (farm-gate value) to the economy. More than 90% of tea tree oil produced in Australia is exported.

The four species of macadamia (*Macadamia*) are listed threatened species native to subtropical rainforests in south-eastern Queensland and north-eastern New South Wales. *Macadamia integrifolia, M. tetraphylla* and their hybrids are grown in plantations in Australia and overseas to produce macadamia nuts. In 2020, Australia had an estimated 11 million macadamia trees in an area of 33 thousand hectares, with around 50 thousand tonnes of nut-in-shell produced yearly, giving a farm gate value of $A280 million[2] (see also Topp 2019).

Tourism (both domestic tourism and, except for a recent hiatus, international tourism) is an important part of the economy for Australia, contributing 2.5% to Australia's GDP in 2019-2020, including in Australia's forested World Heritage sites, forested national parks and other forested areas[3]. An average of 4.2 million people per year visited major forested tourism regions for bushwalking alone in the period 2011-2016 (MIG and NFISC 2018).

Australia has the oldest continuous Indigenous culture in the world, and many Australian native forest species are traditional foods and medicines for Indigenous peoples. Many forested national parks are co-managed by Indigenous traditional owners, and other areas of forest on

[2] australianmacadamias.org/industry/about/about-the-macadamia-industry; australianmacadamias.org/industry/facts-figures/australian-macadamias-year-book-2020

[3] tra.gov.au/data-and-research/reports/national-tourism-satellite-account-2019-20/national-tourism-satellite-account-2019-20

Indigenous-owned lands are managed by Indigenous traditional owners (MIG and NFISC 2018). In 2016, a total of 337 Indigenous people were employed in conservation or park operation roles in areas with forested conservation reserves (MIG and NFISC 2018).

1.3.3 Environmental values

Australia's forests have extremely high conservation value due to their biodiversity. Australia is one of 17 megadiverse countries, and is estimated to have 10% of the world's biodiversity (Department of the Environment and Heritage undated).

Forests in Australia contribute significantly to carbon sequestration. During the period 2011–16, the land-use, land-use change and forestry sector was responsible for net sequestration of carbon dioxide, to an amount that offset 3.5% of total human-induced greenhouse gas emissions for this period from all sectors in Australia. This was primarily due to sequestration through forest growth and forest management practices exceeding emissions from activities such as land clearing for agriculture and infrastructure. In total, a stock of 21,949 million tonnes of carbon was held in Australia's forests at the end of June 2016 (MIG and NFISC 2018).

Forests are important for soil conservation, because they contribute directly to soil production and maintenance, and prevent or reduce soil erosion. Forests are also an important component of water quality provision in many Australian water catchments, and contribute reliable supplies of high-quality water to many major cities (MIG and NFISC 2018). Forested catchments are valuable sources of drinking water because forest vegetation, soil and litter serve as natural filters, and the quality of water flowing from such catchments is usually higher than from non-forested catchments.

1.4 Use of Australia's forest species

Australia has a total of approximately 2,500 native tree species, some 200 of which are of current commercial significance in Australia or overseas (Singh et al. 2013). However, only a small proportion (estimated at 5-10%) of Australian tree species have been studied for their potential for commercial utilisation.

Over 50 Australian eucalypt and acacia species are harvested commercially for wood and wood products (sawlogs and pulplogs) in native forests and/or in plantations in Australia and overseas. **Table 1** lists the main tree species which are harvested for timber (sawlogs) from native forests in Australia. The major native species grown in plantations in Australia for sawlogs or pulplogs are a variety of eucalypts (from the genera *Eucalyptus* and *Corymbia*), hoop pine (*Araucaria cunninghamii*) and Australian sandalwood (*Santalum spicatum*). **Chapter 9** provides further information on the main native and exotic tree species grown in plantations in Australia. **Appendix B** gives information on the uses of species on the FAO list of forest genetic resources for Australia.

Although the majority of forest genetic resources in Australia are used for wood production, some species are used for other purposes. This includes blue mallee (*Eucalyptus polybractea*) for biomass and eucalypt oil, tea tree (*Melaleuca alternifolia*) for oil, macadamia (*Macadamia integrifolia* and *M. tetraphylla*) for nuts, and lemon myrtle (*Backhousia citriodora*) for oil and dried leaves. Other species are used on a commercial basis for fuelwood or for fodder (such as *Atriplex nummularia*), or for Indigenous traditional use.

Several forest species used to produce food items on a commercial basis have been registered with Food Standards Australia New Zealand (FSANZ): mountain pepper (*Tasmannia lanceolata*) for leaf and berry, anise myrtle (*Syzygium anisata*) for leaf and oil, and finger limes (*Citrus* *australasica*), riberry (*Syzygium leuhmannii*), Davidson plum (*Davidsonia* spp.) and lemon aspen (*Acronychia acidula*). A small number of other forest species are harvested or grown commercially for food or medicinal properties, including duboisia (*Duboisia myoporoides*), leatherwood (*Eucryphia lucida*) and Kakadu plum (*Terminalia ferdinandiana*).

Table 1 Main timber species harvested from native forest in Australia

Common name	Scientific name	Listed as forest genetic resources by the FAO
Victoria and Tasmania		
Mountain ash	*Eucalyptus regnans*	Yes
Messmate, stringybark	*E. obliqua*	Yes
Alpine ash	*E. delegatensis*	Yes
Shining gum[a]	*E. nitens*	Yes
Mountain grey gum	*E. cypellocarpa*	No
Brown barrel, cuttail	*E. fastigata*	No
New South Wales and Queensland		
Silvertop ash	*E. sieberi*	Yes
Flooded gum[a]	*E. grandis*	Yes
Dunn's white gum[a]	*E. dunnii*	Yes
Blackbutt[a]	*E. pilularis*	Yes
Spotted gum	*Corymbia maculata* & *C. citriodora*	Yes
Red ironbark	*E. sideroxylon*	Yes
Broad-leaved red ironbark	*E. fibrosa*	No
Narrow-leaved red ironbark	*E. crebra*	No
River red gum	*E. camaldulensis*	Yes
Grey box	*E. woollsiani* & *E. moluccana*	Yes (*E. moluccana*)
White mahogany	*E. acmenoides*	No
Gympie messmate	*E. cloeziana*	Yes
Tallowwood	*E. microcorys*	No
Brush box	*Lophostemon confertus*	No
Cypress pine	*Callitris glaucophylla (*previously *C. columellaris*)	Yes
Hoop pine [a]	*Araucaria cunninghamii*	Yes
Western Australia		
Jarrah	*E. marginata*	Yes
Karri	*E. diversicolor*	Yes
Marri	*Corymbia calophylla*	No
Northern Territory		
Darwin woollybutt	*E. miniata*	No
Darwin stringybark	*E. tetrodonta*	No

[a] Also harvested from plantations
Source: ABARES

Forest species are also a source of potential new products. For example, *Fontainea picrosperma* has become of commercial interest following the recent discovery of a putative anti-carcinogenic agent in its seeds (Grant et al. 2017). A range of other Australian forest species have been analysed for anti-obesity, anti-inflammatory, food preservative, antimicrobial (Sultanbawa and Sultanbawa 2016) and cosmetic applications (MacTavish-West 2016).

Several Australian species on the FAO list of forest genetic resources for Australia (**Appendix B**) are important internationally for wood, shelter, tannin, seeds and fuelwood. Eucalypts are grown worldwide for wood, oils, soil conservation and other purposes, in both plantations and agroforestry systems. There are over 2 million hectares of plantations of Australian wattles (*Acacia*) in southeast Asia and southern Africa, which produce wood pulp worth around $US4.3 billion per year (Griffin et al. 2011) as well as logs for a solid-wood products industry. Tannin is produced from *A. mearnsii* in South Africa and Brazil. Australian *Acacia* species are integrated into agroforestry systems in Africa and elsewhere to produce seed, fodder, fuelwood and poles, and *Acacia saligna* is used to control drifting sand, with about 600 thousand hectares established worldwide (Griffin et al. 2011).

1.4.1 Species listed by FAO as forest genetic resources for Australia

A total of 129 forest tree and woody shrub species and hybrids (126 species and three hybrids) are listed by the FAO as forest genetic resources for Australia. Of these, 115 are native to Australia and 14 are exotic. The hybrids are:

- *Pinus elliottii elliotti* x *Pinus caribaea* var. *hondurensis* (PEE x PCH), developed and grown in plantations in Queensland
- two natural hybrids (*Acacia mangium* x *A. polystachya* and *Eucalyptus saligna* x *E. botryoides*) that are found in the wild.

Detailed information on the attributes and uses of species on the FAO list of forest genetic resources for Australia is provided in **Appendix B, Table 17**.

1.5 Sustainable development

The sustainable use of forest genetic resources in Australia is achieved through considering environmental, social and economic factors. The Australian, state and territory governments, research organisations, conservation agencies, the commercial forestry sector, and the wider community all contribute to the conservation, sustainable use and development of forest genetic resources.

A representative range of forest ecosystems is conserved within Australia's National Reserve System or protected on other land, which supports the conservation of forest genetic resources (see **Chapter 6**). Codes of practice regulate economic uses of forest such as tourism or wood harvesting, and social considerations increasingly address both Indigenous and non-Indigenous usage of forest.

Australia's forest genetic resources play an important role in maintaining and improving forest productivity. Australian forest species have adapted to a wide range of environments, climates and soil types, which has provided both between-species and within-species genetic diversity that can be utilised for environmental conservation and for productive human purposes. Research is currently underway to select forest tree genotypes that are better suited to future projected warmer and drier conditions, and that are resistant or tolerant to increases in the abundance, severity and diversity of pests, diseases and weeds associated with predicted climate change.

1.6 Priorities and constraints

Australia is working to maintain and enhance the contribution, value and importance of forest resources through:

- better communicating the values of forests to the public, including their contribution to the economy and society, and their role in offsetting greenhouse gas emissions

- better communicating how existing forests are managed, and new forests are established, to ensure the future value of these forests is understood
- acting to understand the susceptibility of forest species to current and emerging threats from pathogens, climate change and changing bushfire regimes, and the role of genetic diversity in providing resilience
- acting to mitigate the impact of tourism and urban and rural development on forests
- enhancing the productivity of plantations, maintaining the plantation estate and adapting the sector to future changes in markets
- ongoing genetic improvement and breeding programs for plantation species.

2 State of forests

2.1 Key points

- Australia contains 134 million hectares of forests, including 132 million hectares of native forests. By ownership, most of Australia's native forests (88 million hectares) are in private and leasehold tenures.
  - A total of 46 million hectares of Australia's native forest is on land protected for biodiversity conservation, or where biodiversity conservation is a specified management intent.
  - A total of 37 million hectares of Australia's forests are managed primarily for protective functions including protection of soil and water values.
- Australia's forest policy and management is underpinned by legal, institutional and economic frameworks at the national and the state and territory levels. Sustainable management in public and private native forests includes regulatory controls on harvest, regeneration and forest use.
  - Two schemes certify forest management and provide chain-of-custody certificates for tracking wood products in Australia.
- The most recent data on Australia's forests is compiled in *Australia's State of the Forests Report 2018*. This provides information against 44 indicators of sustainable forest management organised under seven criteria (biological diversity, productive capacity, ecosystem health and vitality, soil and water resources, contribution to carbon cycles, socio-economic benefits and management frameworks).
- Trends and drivers for change in Australia's forests and their genetic resources include continuing impacts from pests, diseases and introduced flora and fauna; climate change and associated higher temperatures, decreased rainfall in some areas, and increased fire occurrence and intensity; and continuing urban development and land clearing for agriculture.
  - These trends and drivers create challenges and opportunities for the conservation, use and development of forest genetic resources in situ and ex situ, and increase the need for genetic improvement and adaptation of tree species to cope with increasing stressors.

2.2 State of the forests in Australia

A forest is defined in Australia (ABARES 2020a) as:

> An area … dominated by trees having usually a single stem and a mature or potentially mature stand height exceeding 2 metres and with existing or potential crown cover of overstorey strata about equal to or greater than 20%.

This definition is different from the definitions of forest that apply in some other countries, or the definition used by the FAO (FAO 2018). Specifically, Australia defines forest as a type of vegetation cover, whatever its land use, whereas the FAO definition of forest excludes land used for agriculture, even if that land carries forest vegetation.

Information on the state of Australia's forests is available in *Australia's State of the Forests Report 2018* (MIG and NFISC 2018).

2.2.1 Area of Australia's forests

Australia has 134 million hectares of forest as at 2016, comprising 132 million hectares of native forest, 1.8 million hectares of commercial plantation forest (Legg et al. 2021) and 0.5 million hectares of other forest (mostly non-commercial plantations, and planted forests of various types) (MIG and NFISC 2018). Australia has approximately 3% of the world's forests, and globally is the country with the seventh largest forest area.

Australia's native forests are dominated by eucalypt forests (101 million hectares) and acacia forests (11 million hectares); there are smaller areas of rainforest and other forest types. The majority of native forests (91 million hectares) are woodland forests with 20-50% canopy cover; there are 34 million hectares of open forest with canopy cover 50-80%, and 3.6 million hectares of closed forests with canopy cover 80-100%.

By tenure, 41 million hectares of Australia's native forests are on private land, 47 million hectares on leasehold land, and the remaining 43 million hectares are on a range of public land tenures (MIG and NFISC 2018). The area of native forest in formal nature conservation reserves is 22 million hectares, and the area of native forests on multiple-use public forest tenure is 10 million hectares.

The area of forest over which Indigenous peoples and communities have ownership, management or special rights of access or use (the 'Indigenous forest estate') is 70 million hectares (Jacobsen et al. 2020b). Both Indigenous and non-Indigenous heritage sites are protected in Australia's forests.

2.2.2 Forest management

Australia's forest policy and management is underpinned by legal, institutional and economic frameworks at the national and the state and territory levels. These frameworks are guided by the *National Forest Policy Statement*[4], and include policy and legislative instruments, and codes of forest practice.

A total of 46 million hectares of Australia's native forest on public and private land is protected for biodiversity conservation, or has biodiversity conservation as a specified management intent. Part of this area is contributed by Australia's National Reserve System. A total of 37 million hectares of Australia's forests are managed primarily for protective functions including protection of soil and water values, such as forested catchments managed specifically for water supply. Some areas are managed for both biodiversity conservation and protective functions (MIG and NFISC 2018).

Wood and non-wood products from Australia's forests make a substantial contribution to the economy and to society more generally. An increasing proportion of Australia's wood is produced in plantations. Commercial plantations are managed on long rotations for sawn timber (mostly softwood plantations of exotic pine species), or on short rotations for pulpwood (mostly hardwood plantations of native eucalypt species).

The net harvestable area of multiple-use public native forests was 5.0 million hectares in 2015-16, and the area of multiple-use public native forest from which wood was harvested in that year was 73 thousand hectares (MIG and NFISC 2018).

Sustainable management in public and private native forests includes regulatory controls on harvest, regeneration and forest use. The volume of sawlogs harvested from public native forests

[4] awe.gov.au/agriculture-land/forestry/policies/forest-policy-statement

in the period 2011–12 to 2015–16 was within sustainable yield levels in New South Wales, Tasmania, Victoria and Western Australia, and was within the allowable cut in Queensland (MIG and NFISC 2018). The sustainable yield from multiple-use public native forests has declined over time, due to the transfer of multiple-use public native forests into nature conservation reserves, increased restrictions on harvesting, revised estimates of growth and yield, and the impacts of occasional, intense broad-scale bushfires.

Two schemes certify forest management and provide chain-of-custody certificates for tracking wood products in Australia. As at September 2021, 16.3 million hectares of native forests and plantations were certified under the Responsible Wood Certification Scheme and endorsed under the Programme for the Endorsement of Forest Certification[5], while 1.2 million hectares were certified under Forest Stewardship Council scheme[6].

2.2.3 Condition of Australia's forests

The extent to which ecosystem services are delivered from forests varies with forest type, growth stage, the degree of fragmentation of the forest, climatic conditions, and as a result of the impacts of fire, pests and diseases. Australia's native forests comprise stands at regeneration, regrowth, mature and senescent growth stages, as well as stands of uneven-aged forest.

The fire regime (the intensity, frequency, scale and spatial arrangement of fire) is one of the key drivers of the state of Australia's forests, including their age-class structure. Planned fire is used as a forest management tool in fire-adapted forest types for forest regeneration, to promote regeneration after harvest, to maintain forest health and ecological processes, and to reduce fuel loads and thereby increase the ability to manage bushfires and protect vulnerable communities.

Over the period 2011–12 to 2015–16, the annual area of fire in Australia's forests varied from 15 million hectares in 2015–16, to 27 million hectares in 2012–13 (MIG and NFISC 2018). The cumulative area of fire in forest across this period (the sum of the forest fire areas for each of the five years) was 106 million hectares, of which 69% was unplanned fire. However, when areas of forest burnt in multiple years are allowed for, the total area of forest burnt one or more times during this period was 55 million hectares (41% of Australia's total forest area). The balance (59% of Australia's forest area) did not experience fire in this period.

In the Australian 2019-2020 'Black Summer' bushfire season, bushfires in southern and eastern Australia were unusually extensive following an extended drought. In total, these bushfires burnt 10.3 million hectares of land including 8.5 million hectares of forest[7].

Forest fragmentation describes the extent to which forest areas are separated by or adjoin non-forest areas, and can be natural or of human origin. The majority of Australia's native forest forms continuous areas, rather than being fragmented. A total of 68% of Australia's native forest is in patches of over 100 thousand hectares, while at the 1-hectare scale 72% of Australia's native forest comprises areas that are completely bounded by forest (MIG and NFISC 2018).

Native forest that is not fragmented is found in forested areas of higher rainfall, as well as in regions that have experienced the least clearing for agricultural land use, and in nature conservation reserves. More fragmented forests occur in drier regions where woodland forest

[5] responsiblewood.org.au/; area data from cdn.pefc.org/pefc.org/media/2021-08/725619c9-2460-4061-866d-95e160251648/22bd782f-bd0d-5840-a4bb-843400f15bea.pdf
[6] au.fsc.org/en-au; area data from fsc.org/en/facts-figures
[7] awe.gov.au/abares/forestsaustralia/forest-data-maps-and-tools/fire-data

naturally borders areas of non-forest vegetation, and in areas with higher impacts from historical land clearing for agriculture and urban development

The carbon stock in Australia's forests in 2016 was 21,949 million tonnes, an increase of 0.6% since 2011 (MIG and NFISC 2018). This increase was due to a combination of recovery from past clearing, additional growth of plantations, reduced clearing of native forest, expansion of the area of native forests, and continued recovery from bushfire and drought.

There are at least 16,836 native vascular flora species (plants) in Australia's forests (MIG and NFISC 2018). Of these, 1,074 are listed as threatened species under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Seventeen of the species on the FAO list of forest genetic resources for Australia are listed as threatened under the EPBC Act.

Based on the listing advice documents, the most common threats to nationally listed forest-dwelling fauna and flora are forest loss from clearing for agriculture and urban and industrial development; impacts of predators; small population sizes; and unsuitable fire regimes (MIG and NFISC 2018). Forestry operations pose a less significant threat to nationally listed forest-dwelling fauna and flora species compared with other threat categories.

2.3 Trends, drivers and consequences

Australia's forests are subject to a range of pressures, including extreme weather events, drought and climate change; invasive weeds, pests and diseases; changed fire regimes; and clearing for urban development, mining, infrastructure or agriculture. These pressures can threaten native forest genetic resources, including through loss of tree species in conservation areas or in ex situ plantings. Legacy effects from historical land clearing and forest fragmentation for agriculture and urban expansion also exist.

Australia's forest area has increased progressively since 2008. This has been due to the net effect of various factors: forest clearing or reclearing for agricultural use, regrowth of forest on areas previously cleared for agricultural use, expansion of forest onto areas not recently containing forest, establishment of environmental plantings, and changes in the commercial plantation estate. In each year of the period 2011–2016, the area of forest cleared or recleared was less than the area of forest regrowing from previous clearing. The net increase in forest area over the period 2011-2016 was 3.9 million hectares (MIG and NFISC 2018).

The number of species listed as threatened under the EPBC Act continues to be updated, with new forest species added and removed from the national list during the period 2011-2016 (see **Chapter 4**).

Myrtle rust was first detected in Australia in 2010 and is now present in all states and territories except the Australian Capital Territory, South Australia and Western Australia. Subtropical wet sclerophyll forest or rainforest communities that have mid-storey and understorey layers rich in species of the Myrtaceae family are being severely altered by myrtle rust, which has caused defoliation, dieback and death of trees of some rainforest species. Populations of two widespread species, *Rhodamnia rubescens* and *Rhodomyrtus psidioides*, are in rapid local decline (see **Chapter 4**).

There has been a sustained shift in the Australian climate since 1970. A drier and hotter climate in southern Australia has led to the frequency of severe fire weather days increasing in recent decades across many regions[8], which extends the duration of the fire season, reduces the interval between fires, and reduces the opportunity for planned fire (Read and Lehmann 2020).

2.4 Challenges and opportunities

The above trends and drivers create challenges and opportunities for the conservation, use and development of forest genetic resources. As an example, various conservation efforts and community partnerships are aimed at improving forest connectivity in Australian landscapes, to improve ecosystem health, gene flow and the scope for species adaptation (see **Chapter 7**). Changes in the climate have prompted work to develop adaptation strategies to help mitigate adverse effects, and management that takes account of bushfire risks has become more critical across southern Australia due to the impacts of both climate change and increasing urbanisation.

More stressful environmental conditions also increase the need for adaptation and genetic improvement of plantation tree species.

[8] reg.bom.gov.au/state-of-the-climate/

3 State of other wooded lands

3.1 Key points

- The FAO definition of 'Other wooded lands' (FAO 2018) is most similar to the Australian vegetation category 'Other woody vegetation'. This is a non-forest vegetation type of open woodland, heathland or shrubland that generally contains a tree component with actual or potential tree height greater than 2 metres, but tree crown cover of only 5–20% (ABARES 2020a).
- As a non-forest vegetation, other woody vegetation is not reported in the *Australia's State of the Forests Report* series, and there is no national compilation of data on other wooded lands or their genetic resources.
    - Some tree and woody shrub species found in Australian forests also occur in 'Other woody vegetation'.
- Other woody vegetation is also called 'Sparse woody vegetation'. Changes in the area of sparse woody vegetation are reported in Australia's National Inventory Reports for emissions accounting purposes (Australian Government 2021)[9].

[9] industry.gov.au/data-and-publications/national-inventory-reports

4 State of diversity between trees and other woody plant species (species diversity)

4.1 Key points

- Australia has a high diversity of forest species, including many endemic species.
  - There are at least 16,836 native vascular flora species (plants) in Australia's forests, including approximately 800 eucalypt species and almost 1,000 acacia species.
- Australia's native forests are dominated by eucalypt and acacia forests with smaller areas of other forests. Although rainforests comprise only 3% of Australia's total native forest area, they provide habitat for 60% of Australia's plant species.
- There are 129 tree species and hybrids listed by the FAO as forest genetic resources for Australia, of which 115 species and hybrids are native.
- As at 2016, a total of 1,074 forest vascular plant species are listed as threatened under Australia's *Environment Protection and Biodiversity Conservation Act 1999*, including 17 species or subspecies on the FAO list of forest genetic resources for Australia.
  - The key threats to forest species are loss, degradation and fragmentation of habitat, invasive species and altered fire regimes.
  - During the period 2011–16, a total of 68 forest-dwelling species were added to the national list of threatened species, and 77 forest-dwelling species were removed. Most additions were based on inherently small population sizes or ongoing impacts on habitat extent and quality, while most removals resulted from information that species were no longer considered valid species or were not threatened.

4.2 Species diversity in Australia

Australia has a diverse and rich forest flora, with high levels of endemism and many rare species. Australia is one of 17 megadiverse countries and it is estimated to contain 10% of the world's biodiversity[10]. Information on Australia's plant species and their distribution can be found in Chapman (2009) as well as databases and reference collections such as Atlas of Living Australia (ALA)[11] and the Australian National Herbarium (ANH)[12].

The ALA is Australia's national biodiversity database, supported by the Australian Government through the National Collaborative Research Infrastructure Strategy and hosted by CSIRO, and is a node of the Global Biodiversity Infrastructure Facility. It collates data on species and environments from state and national herbaria and other collections and observations. These data include occurrence records, images, species conservation status, and environmental data. Species distributional data are represented using online mapping.

[10] awe.gov.au/environment/biodiversity/publications/genetic-resources-management-commonwealth-areas
[11] ala.org.au/
[12] anbg.gov.au/cpbr/herbarium/

The ANH stores a national reference collection of Australia's plants, and represents the amalgamation of CSIRO herbaria, the Forest Research Institute Eucalypt Collection, the Forest Research Institute's Atherton Rainforest Collection, and the Australian National Botanic Gardens Herbarium. Combined with information from state and territory herbaria and other collections, the ANH presents knowledge on the distribution of most of Australia's forest species.

4.2.1 Forest plant diversity

An important measure of species diversity is the number of forest-dwelling species, which are species that may use forest habitat for all or part of their lifecycles. Information on Australia's forest-dwelling species (flora and fauna) is assembled in Indicators 1.2a-c and Indicator 1.3a of *Australia's State of the Forests Report 2018* (MIG and NFISC 2018).

There are at least 16,836 forest-dwelling plant species in Australia (Davey 2018b; MIG and NFISC 2018). This number is known to be a significant underestimate, and is currently being updated. It includes approximately 800 species of eucalypts and almost 1,000 species of acacia. Almost all eucalypt species are native to Australia.

Australia's native forests are classified into eight forest types: Acacia, Callitris, Casuarina, Eucalypt, Mangrove, Melaleuca, Rainforest and Other native forest (MIG and NIFSC 2018). These forest types, and the diversity of species within them, reflect Australia's wide variation in climate, latitude, soil and environmental factors. More information on Australia's forest types is found in the *Australian forest profiles* published by ABARES[13].

The dominant native forests in Australia are Eucalypt[14] and Acacia[15] forests, with smaller areas of other forest types. Although Rainforest[16] comprises only 3% of Australia's total native forest, this forest type provides habitat for 60% of Australia's plant species, 60% of butterfly species, 40% of bird species and 35% of mammal species.

4.3 Species distribution

Some forest species in Australia are widespread, such as *Eucalyptus camaldulensis* and *Acacia ligulata*. Other species have a very restricted distribution, such as *Wollemia nobilis*, which has only one population consisting of several stands of fewer than 100 adult plants and 200-300 juveniles/seedlings (Department of Environment and Conservation NSW 2007).

The Atlas of Living Australia (ALA)[17] contains Australian distribution information for all 126 species (excluding hybrids) listed by the FAO as forest genetic resources for Australia. Specimens for each species have been lodged in herbaria, supplemented by survey data and individual observations. In the last ten years, new observations for all native species on the FAO species list of Australia's forest genetic resources have been formally recorded.

4.4 Threatened species diversity

As at 2016, a total of 1,420 forest-dwelling species were listed as threatened species under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) (Davey 2018c; MIG and NFISC 2018). Of these, 1,074 are vascular flora species, and one is a

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[13] awe.gov.au/abares/forestsaustralia/profiles
[14] awe.gov.au/abares/forestsaustralia/profiles/eucalypt-2019
[15] awe.gov.au/abares/forestsaustralia/profiles/acacia-2019
[16] awe.gov.au/abares/forestsaustralia/profiles/rainforest-2019
[17] ala.org.au/

non-vascular flora species. Further information on institutional arrangements to manage threatened species is provided in **Chapter 11**.

Of Australia's forest-dwelling fauna and flora species listed as threatened under the EPBC Act, 57% have genetic-related reasons contributing to their listing (MIG and NFISC 2018). This includes species with small or fragmented populations, or that have low genetic variability.

During the period 2011–16, a total of 68 forest-dwelling species were added to the national list of threatened species, and 77 forest-dwelling species were removed. Most additions were based on inherently small population sizes and/or ongoing impacts on habitat extent and quality, including impacts of introduced species and unsuitable fire regimes. Most removals of listed species were a result of improved information that indicated that species were no longer considered valid species or were not threatened.

There are 37 plant species listed as extinct under the EPBC Act, including Daintree's River banana (*Musa fitzalanii*), *Acacia kingiana* and several other woody plant species collected in the late 1800s and early 1900s, potentially from forests[18]. Other plant species are listed as presumed extinct under state and territory legislation. No plant species have been listed as extinct under the EPBC Act since 2001, but 201 flora species are listed as critically endangered.

Australia's main plantation species, and the majority of other tree species of economic and social importance, are not threatened species. Seventeen of the species on the FAO list of forest genetic resources for Australia are listed, in whole or part, as threatened under the EPBC Act (**Table 2**).

Table 2 Species on the FAO list of forest genetic resources for Australia that are listed as threatened under the EPBC Act

Species	Taxonomic level below species used in EPBC listing	EPBC listing
Acacia cochlocarpa	subsp. *cochlocarpa*	Endangered
	subsp. *velutinosa*	Critically endangered
Callitris oblonga		Vulnerable
	subsp. *oblonga*	Endangered
Davidsonia jerseyana		Endangered
D. pruriens		Endangered
Eucalyptus argophloia		Vulnerable
E. benthamii		Vulnerable
E. burdettiana		Endangered
E. conglomerata		Endangered
E. crenulata		Endangered
E. gunnii	subsp. *divaricata*	Endangered
E. kartzoffiana		Vulnerable
E. morrisbyi		Endangered
E. raveretiana		Vulnerable
E. scoparia		Vulnerable
Macadamia integrifolia		Vulnerable
M. tetraphylla		Vulnerable
Wollemia nobilis		Critically endangered

Source: Species Profile and Threats Database, EPBC Act List of Threatened Fauna, environment.gov.au/cgi-bin/sprat/public/publicthreatenedlist.pl

[18] environment.gov.au/cgi-bin/sprat/public/publicthreatenedlist.pl?wanted=flora#flora_extinct

4.4.1 Drivers and threats to species diversity

The key threats to forest species are loss, degradation and fragmentation of habitat, invasive species and altered fire regimes.

For listed threatened forest-dwelling flora, the most common threat categories are small population size and localised distribution, followed by mortality agents (including illegal collection, recreational pressure, pressures from peri-urban development, and genetic or breeding issues) and unsuitable fire regimes (MIG and NFISC 2018).

Human-induced habitat fragmentation reduces connectivity and can alter ecological processes of reproduction and dispersal, leading to changes in genetic diversity. Habitat fragmentation is discussed further in **Chapter 5**.

Australia has a large number of introduced (exotic) species, including some that can affect native forest and plantation health and species viability.

Myrtle rust was first detected in Australia in 2010, and is now present in most Australian states and territories. At least 358 taxa have been observed to be susceptible to myrtle rust infection, and an estimated 45 species are known or suspected to be in decline (Makinson 2018). The disease is severely affecting some Myrtaceae species in subtropical wet sclerophyll forest or rainforest communities. Populations of two widespread rainforest species, *Rhodamnia rubescens* and *Rhodomyrtus psidioides,* that were relatively common in 2010, are in rapid decline and now listed as critically endangered in New South Wales. While seed storage, tissue culture and grafting trials are feasible for these two species, they now produce few viable seeds in the wild; conservation by seed-banking will first require the establishment of a seed orchard from vegetatively propagated plants (Sommerville et al. 2020).

In the Australian 2019-2020 bushfire season, known as the 'Black Summer', bushfires in southern and eastern Australia were unusually extensive following an extended drought. These had a significant impact on the total population of a number of threatened species, with these impacts likely also having genetic consequences (Dickman 2021).

5 State of diversity within trees and other woody plant species (genetic diversity)

5.1 Key points

- A range of Australian forest species have been characterised for within-species diversity using non-molecular and molecular techniques:
    - Non-molecular techniques such as provenance trials and ecological research continue to be used to characterise within-species variation in forest plants.
    - There is also increasing use of molecular techniques, DNA markers and genomics, with over 200 forest-dwelling plant species genetically characterised using molecular techniques, including 76 species on the FAO list of forest genetic resources for Australia.
    - All major plantation species have been genetically characterised to some extent, but understanding of the breeding system, fecundity and between-population genetic variation in other Australian forest species is more limited.
- Allozyme and microsatellite studies of Australian plant species show that range size, growth form, abundance and biome have the greatest effect on genetic diversity. Other factors include breeding system, seed dispersal type, previous glacial cycles, and historical ecogeographic barriers to gene flow.
    - A range of plant species from south-western Western Australia and from eastern Australian rainforest have low genetic diversity, possibly as part of adaptation to specific habitats and niches.
- The lack of longitudinal studies makes it difficult to identify trends over time in genetic diversity.
- Threats to within-species diversity include land clearing, habitat fragmentation, climate change, and increased intensity, frequency and extent of landscape-scale bushfires.
    - Listing advice documents identified conservation concerns about population size, isolation, or altered genetic capacity for 747 of the 1,074 forest vascular plant species listed as threatened in Australia as at June 2016.
    - Several studies have demonstrated altered breeding processes or reduced seed viability in fragmented populations of forest species.
    - For some rare species, potential threats include pollination contamination from nearby plantations.
- Key capacity-building and research needs with regard to genetic diversity in forest species include:
    - training for scientists and ongoing research in genetics
    - characterising priority species
    - investigating genetic effects of forest fragmentation on species over time
    - identification and maintenance of climate refugia for species
    - incorporation of climate change predictions into selection of provenance and seed sources for revegetation, tree breeding programs and species translocation
    - improved communication with policy makers and the public about the importance of genetic conservation and management.

5.2 Importance of genetic diversity within species

Forests in Australia are present in a wide range of environments, reflecting Australia's varied climates, geography and soil types. Some forest species are widespread, including several of the tree species used for plantation forestry. Many other species have regional or localised distributions (**Appendix B, Table 17**). The large area and diversity of Australian environments means that characterising species genetic diversity is challenging.

Information on the genetic diversity and genetic structure of species can be used to inform conservation policy, conservation activities, species management, and tree improvement programs. Conserving the genetic variation within species is important for forest productivity, health and adaptability.

5.3 Institutions and technologies for species genetic characterisation

Over several decades, a range of Australian organisations have conducted research to characterise the genetic diversity of Australian plant species, in particular CSIRO, universities, and government forestry and conservation departments.

A wide range of timber species and some other forest species have been characterised in Australia, through provenance trials or research studies on ecological variation, climatic zonation or disease resistance. For example, morphological (physical) variation within species growing along a cline or ecological gradient has been characterised within *Eucalyptus viminalis*, *E. globulus* and *E. pauciflora* populations (Ladiges 1974; Hamilton et al. 2013; Young et al. 2018). Chemical analyses of leaf tissue have been used to examine oil yield (e.g. Padovan et al. 2017a,b), plant defences (e.g. Andrew et al. 2007), differential palatability of trees (e.g. Wallis et al. 2002), and indicate the evolutionary history of related species (e.g. Robertson et al 2018). Many planted trials have been used to compare growth and form of provenances within a species (e.g. *E. nitens*, Pederick 1979; *E. dunnii*, Arnold et al. 2004).

Over the past 20-25 years, molecular technologies have been used increasingly in Australia and overseas to characterise species genetic diversity, particularly as techniques and the cost of analysis improved. During this time, technologies have shifted from allozyme analysis to DNA markers and, more recently, the characterisation of whole species genomes. Analyses of Quantitative Trait Loci (QTLs) and single nucleotide polymorphisms (SNPs) allow tree-breeding to be assisted by Marker-Assisted Selection (MAS). New sequencing technologies are also rapidly enhancing the ability to carry out genomic selection and introgress adaptive traits in many crops worldwide, including increasingly in forest and horticultural trees (King G, Southern Cross University, pers. comm. 2021).

5.3.1 Datasets and databases

Previously, the CSIRO database TREDAT held national data on a large number of species and provenance trials (921 taxa), but the system is no longer available (Booth 2018). Currently, knowledge from non-molecular characterisation of within-species diversity (provenance and other trials) is not formally inventoried at a national or sub-national level, but some state government and industry databases hold provenance data for some species.

Knowledge from molecular characterisation is also not formally inventoried at a national scale. However, reviews by Moran (1992) and Broadhurst et al. (2017) cite many published Australian molecular studies on plants, and molecular and genomic data are being captured by various projects and databases:

- Around 26 eucalypt genomes have now been deposited in the National Center for Biotechnology Information (NCBI), USA (King G, Southern Cross University, pers. comm. 2021).
- DNA/RNA and protein sequences are held in the QFAB bioinformatics database[19]
- A running tally of sequenced plant genomes including Australian taxa is maintained by the *Genomics for Australian Plants Framework Initiative*[20].
- The recently established DivSeek International[21] intends to store and share information on genome characterisation.

5.4 Overview of genetic diversity research on forest species in Australia

More than 200 Australian forest plant species have been examined over the past four decades for population genetic variation using molecular techniques, including 76 of the species listed by FAO as forest genetic resources for Australia. This is only a small proportion of Australia's plant species. Most genetic diversity work has been done on species used in commercial forestry, and on threatened species. **Appendix A** shows the species listed by FAO as Australian forest genetic resources that have been genetically characterised using non-molecular or molecular techniques. **Appendix B** details the uses of these species.

All major Australian plantation species have been genetically characterised to some extent. Some Australian rainforest species have also been characterised (e.g. Shapcott and Playford 1996; Rossetto et al. 2007, 2009; Mellick et al. 2011; Thurlby et al. 2012) including macadamia[22]. Only a small number of threatened forest species have been investigated (see for example, the attachment to Broadhurst et al. 2017). Australian forest plantation species have also been genetically characterised overseas.

To inform tree breeding strategies, the genetic diversity of some native plantation timber species, including *E. nitens*, has been analysed for traits such as variability in wood characters and disease susceptibility. Variability in chemotypes has also been studied for species with commercially important essential oils. Further information on tree breeding is provided in **Chapter 9**.

CSIRO, herbaria and various universities continue work on plant species characteristics. For example, current research at the Australian National University includes research on drought tolerance in eucalypts, landscape genomics, and research on pest resistance and sustainable plantation management of eucalypts, including chemical and genetic variation within species[23]. There is ongoing research in Western Australia on its unique flora, in particular rare and disjunct species in both forest and non-forest ecosystems (e.g. Broadhurst et al. 2017).

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[19] researchdata.edu.au/qfab-bioinformatics/59777; see researchdata.edu.au/australian-nucleotide-dnarna-melia-azedarach/53692 for an example

[20] genomicsforaustralianplants.com/compilation-of-sequenced-plant-genomes/; bioplatforms.com/projects/genomics-for-australian-plants/

[21] divseekintl.org/

[22] see for example scu.edu.au/southern-cross-plant-science/people/researchers/dr-catherine-nock/

[23] see for example biology.anu.edu.au/research/themes/phylogenetics-population-genetics-and-biodiversity#acton-tabs-link--tabs-research_theme_tabs-middle-4).

The reference genome sequence for eucalypts was released by an international consortium, including Australians, working on flooded gum (*E. grandis*), a key species for tree breeding worldwide (Myburg et al. 2014). An understanding of the eucalypt genome is expected to improve studies of comparative and evolutionary biology, as well as eucalypt adaptation, and accelerate breeding for productivity and wood quality. The first complete anchored genome of a Proteaceae species, the Australian tree *Macadamia*, was published in 2020 (Nock et al. 2020). In addition, the anchored *Corymbia citriodora* genome has been completed by an Australian and international consortium (Healey et al. 2021).

An Australian national project, the 'Genomics for Australian Plants Framework Initiative', is a network of researchers, data scientists, and state and national government agencies collaborating on the collection, management, dissemination and application of genomic data for Australian native plants[24]. The initial pilot included Australia's floral emblem, *Acacia pycnantha*. The initiative is also partnering in the Kew (United Kingdom)-led PAFTOL (Plant and Fungal Trees of Life[25]) initiative to understand the evolutionary history and relationships between all plant and fungal taxa (King G, Southern Cross University, pers comm. 2021).

5.5 Patterns of within-species genetic diversity in Australian plants

Australia's continent is old, large, relatively flat and has a broad range of biomes (e.g. alpine, temperate woodland, subtropical rainforest, arid and Mediterranean). It has had a long and isolated history with few volcanic or glacial perturbations (Broadhurst et al. 2017). As outlined above and in **Chapter 4**, this has contributed to a phylogenetically diverse and rich flora evolving in Australia, with high levels of endemism. Australia also has a large number of taxa with historically fragmented or disjunct distributions, particularly in south-west Western Australia and eastern Australian rainforest.

Factors which appear to have influenced the genetic diversity within some Australian tree species include historical ecogeographic barriers to gene flow over significant time frames (Moran and Hopper 1987), specialised pollination, breeding systems and fruit dispersal (Rossetto et al. 2009; Broadhurst et al. 2017), and environmental factors associated with altitude. In a comparison of six major eucalypt species (*E. grandis, E. urophylla, E. globulus, E. nitens, E. dunnii* and *E. camaldulensis*), Hudson et al. (2015) concluded that genomic architecture influences patterns of species diversity and divergence.

Broadhurst et al. (2017) reviewed more than 300 molecular studies of Australian plants, of which 290 allozyme and microsatellite datasets across 235 taxa met their requirements for analysing associations between species attributes and genetic diversity. Range size, growth form, abundance and biome had the greatest effect on genetic diversity within Australian plant species, the most important of these being range disjunction and abundance:

- Wide-ranging and more abundant species have greater genetic diversity than plants with small ranges or lower abundance. Species with small, localised ranges are more likely to be influenced by the effects of genetic drift, reducing genetic diversity.
- Species with distributions that include range disjunctions expected to limit gene flow showed a higher level of genetic differentiation than species with non-disjunct

[24] genomicsforaustralianplants.com/
[25] kew.org/science/our-science/projects/plant-and-fungal-trees-of-life

distributions. Disjunct ranges can result from either recent habitat fragmentation or historical ecogeographic barriers.
- There was greater diversity in the eastern biome of Australia (relative to western and tropical biomes), and lower diversity in shrubs compared with trees.
- Australian trees and long-lived woody perennials had greater genetic differentiation than a global analysis. This may be due to the high prevalence of animal and insect pollination in Australian trees, compared with the dominance of wind pollination in temperate/boreal Northern Hemisphere trees. Moran and Hopper (1987) noted the same trend when widespread Australian trees are compared with Northern Hemisphere trees, and suggested that this could also be due to a patchier distribution of widespread Australian trees due to their greater edaphic specialisation.

Most of the major native species used in plantations in Australia have widespread or regional distributions (**Appendix B, Table 17**). In a review of isozyme studies, Moran (1992) found that Australian tree species in the genera *Acacia* and *Eucalyptus* generally have high levels of allozyme variation, with most of this variation being within rather than between populations. Species with regional distributions but with small disjunct populations tended to have the most genetic differentiation between populations.

A range of Australian rainforest tree species have low genetic diversity, and there is some evidence for limited gene flow due to the effects of environmental factors, contrasting evolutionary histories, and breeding and fruit dispersal systems (Rossetto et al. 2004, 2007, 2008, 2009; Mellick et al. 2011; Thurlby et al. 2012). Rossetto et al. (2007) noted that biogeographic features appear to have different impacts on related species, and cautioned against making generalisations about evolutionary patterns; rather, a range of factors must be considered. For example, while *Elaeocarpus largiflorens* has an abrupt genetic disjunction between two subspecies separated by a recognised biogeographic barrier (the Black Mountain Corridor), its congener *E. angustifolius* showed lower genetic differentiation across a much wider geographic area.

Lamont et al. (2016) noted that low levels of genetic diversity in various Australian plants may be an adaptation to harsh environmental conditions (e.g. James 2000, Rossetto et al. 2007, Thurlby et al. 2012), but also result from ancient lineages, such as *Wollemia nobilis* (Peakall et al. 2003). They proposed that purging of genetic variation would allow rainforest taxa and taxa in the south-west Western Australian flora (see James 2000) to become highly adapted over long time periods to specific niches. As a consequence of extreme specialisation and niche differentiation in a stable environment, when environmental conditions change such species could only retreat into the remaining habitat to which they are adapted (Lamont et al. 2016). Adaptation to specific niches may make some species susceptible to loss of genetic diversity following human-induced forest fragmentation.

5.5.1 Genetic diversity in selected forest tree and woody plant species

Eucalyptus camaldulensis is one of Australia's most widespread species, ranging from arid Australia to temperate woodland and open forest at low to medium rainfall. Various provenances have been selected for a range of plantation environments overseas, and used as hybrids in Australia. Butcher et al. (2009) found strong geographic trends in genetic diversity, with 40% of variation explained by latitude and moisture index. They also found significant genetic differences among populations within river systems, which indicated that individual rivers should not be treated as single genetic entities in conservation or breeding programs. Butcher et al. (2009) concluded that isolation by distance and historical environmental factors have had more influence on current patterns of distribution of genetic diversity than evolutionary selection.

Eucalyptus globulus is Australia's most widely planted eucalypt plantation species, and is genetically variable across its native geographic range in Tasmania and Victoria. Total genetic diversity and genetic diversity within localities are consistent with values reported for other eucalypt species with regional distributions (Mitchell et al. 1996). The broad-scale quantitative genetic variation in numerous traits has been summarised by classifying the native gene pool into a hierarchy of 13 races and 20 subraces (Dutkowski and Potts 1999; Cañas et al. 2004). Molecular genetic studies have shown that these genetically differentiated races form three major lineages (Jones et al. 2006; Steane et al. 2006; Jones et al. 2012) or five major clusters (Yeoh et al. 2012).

Eucalyptus nitens (including *E. denticulata*, Cook and Ladiges 1991) is an important plantation species that has a wide range and a disjunct distribution in cool-temperate high-rainfall areas of eastern Australia. Byrne et al. (1998) sampled eight populations covering the natural range of the species, and found a high level of diversity within the nuclear genome. Most of the diversity was maintained within populations. There was significant differentiation between populations, as expected in a species with disjunct populations and limited gene flow. Genetic populations clustered in distinct and separate regions generally concordant with the geographical distribution of the species. The exception was the Errinundra population, situated between the southern New South Wales and the main Victoria populations but genetically distinct from those, and also recognised as a separate species, *E. denticulata*, on morphological grounds (Cook and Ladiges, 1991). Diversity measures were generally lower in the most disjunct two populations from northern New South Wales.

Eucalyptus morrisbyi is an endangered eucalypt, restricted to four populations on the island of Tasmania. The two main populations (Risdon Hills and Calverts Hill) are both in reserves, separated by 20 kilometres, but the small population at Risdon Hills has experienced a marked decline (Jones et al. 2005). There are marked genetic differences between the two main populations, but equally high levels of genetic diversity in the adult trees, and little difference in inbreeding levels despite the large difference in population size. Each main population showed high outcrossing rates, little inbreeding and high genetic diversity in seedling populations. The authors argued that the high genetic diversity maintained in the small Risdon Hills population is due to a combination of genotype longevity, well-developed vegetative regeneration from lignotubers, and high outcrossing rates maintained by a strong self-incompatibility mechanism.

Rare species tend to have lower genetic diversity across their range, relative to more widespread species. For example, Broadhurst and Coates (2002) found that, in south-west Western Australia, the rare and highly restricted *Acacia oldfieldii* had significantly lower levels of genetic diversity compared with the other taxa in the *A. acuminata* complex. However, there may also be greater population structure within rare, historically disjunct or geographically restricted taxa. For example, studies on taxa from several different genera in south-west Western Australia showed unusually high levels of population differentiation (Coates 2000).

The relative genetic diversity of rare species depends on a range of factors. Shapcott and Playford (1996) found that remnant individuals of the extremely rare rainforest understorey species *Austromyrtus gonoclada* had higher genetic variability than populations of three more widespread congeners in south-east Queensland. They suggested this may be a legacy of relatively recent human-induced habitat fragmentation of *A. gonoclada*, before which the individuals were part of a larger population.

The subcanopy rainforest tree *Fontainea picrosperma* from Far North Queensland is locally common, yet has a highly restricted range. Genetic analysis (Lamont et al. 2016; Grant et al. 2019) found comparatively low levels of genetic variation across the species, both among individuals and within populations, but no loss of genetic diversity between adult and juvenile trees. Much of the pollen flow was over short distances, and inbreeding was negligible despite low levels of historical gene flow, presumably due to the dioecious breeding system. It was concluded that *F. picrosperma* was previously more continuously distributed, but that rainforest contraction and expansion in response to glacial-interglacial cycles, together with significant anthropogenic changes, have resulted in significant fragmentation. However, although low genetic diversity is theoretically a prelude to genetic impoverishment, *F. picrosperma* has persisted through multiple significant climatic oscillations. Low genetic diversity occurs in many of the ancient lineages in the Australian rainforest flora.

In Australia, the subtropical to tropical rainforest tree *Castanospermum australe* occurs in multiple disjunct rainforest populations. The species has large seeds within a buoyant, water-dispersed pod. The seed was traditionally eaten by Indigenous peoples after processing to remove the toxins, and anthropological evidence and Indigenous traditional stories and pathways indicate that the seed was probably dispersed by Indigenous peoples (Rossetto et al. 2017). In northern New South Wales, the seed is also eaten by mountain brushtail possum (*Trichosurus caninus*) and bush rat (*Rattus fuscipes*), and the spongy mesocarp within pods may be eaten by rainforest macropods (Lott 1997). There are no known megafauna that might have dispersed the seed historically. Genome analysis by Rossetto et al. (2017) found high levels of genetic differentiation between three adjacent catchments from north Queensland, but genetic homogeneity in the populations in northern New South Wales. This indicated that the sampled northern New South Wales populations are derived from recent dispersal events from one or a small number of very closely related maternal lineages. The authors concluded that Aboriginal-mediated dispersal had led to the uniform genetic structure of the northern New South Wales populations, whereas in northern Queensland dispersal whether by animals or humans does not maintain connectivity among populations.

5.6 Threats to and trends in genetic diversity within species

The populations of many Australian forest species have declined since 1788 as a result of European settlement, subsequent urbanisation, agricultural expansion and other factors, and some species continue to reduce in area or health. For example, there has been a substantial reduction in numbers and health of *Eucalyptus gunnii* subsp*. divaricata* in Tasmania[26]. However, all species listed by the FAO as forest genetic resources for Australia have populations conserved in situ in the formal and informal forest estate (**Chapter 6**), and some species are now protected from clearing or harvesting (**Chapter 10**).

In 2018, a total of 1,075 forest-dwelling flora species (1074 vascular plant species and one non-vascular plant species) were listed as threatened under the Commonwealth Government *Environment Protection and Biodiversity Act 1999* (MIG and NFISC 2018). Of these, 747 species were listed as threatened due to one or more conservation concerns about isolation or genetic capacity, including 667 species due to small population, 275 due to fragmented population, 256 due to low genetic diversity, 9 due to hybridisation, and 334 due to fecundity issues.

[26] awe.gov.au/environment/biodiversity/threatened/conservation-advices/eucalyptus-gunnii-subsp

It is difficult to comment on trends over time in genetic diversity within forest species. Few studies of Australian tree and woody shrub species analyse change in genetic variation through time, and retrospective analyses are rarely feasible because of the lack of sufficient historical population-level samples collected and stored in a way that is amenable to genetic analysis (D Bush and A Young, CSIRO, pers. comm. 2021). In one study, Coates et al. (2015) compared ex situ seed collections and extant populations of the rare endemic species *Banksia browniii*, and found that a substantial proportion of gene diversity and allelic richness had been lost due to the introduced disease *Phytophthora cinnamomi*; the three geographically disjunct population assemblages had significant genetic differentiation.

5.6.1 Habitat fragmentation

Australia has been subject to significant land clearing and habitat fragmentation since European colonisation and more recent human settlement, including in forests and woodlands. Habitat fragmentation is expected to reduce genetic variation within populations, and increase interpopulation genetic divergence, through one or more of reduced population sizes, increased spatial isolation of populations, increased random genetic drift, elevated inbreeding, reduced gene flow between populations, and increased probability of extinction of alleles within small populations (Templeton et al. 1990, Ledig 1992, Young et al. 1996).

However, the genetic effects of habitat fragmentation differ between species, depending on a range of factors including species longevity, generation time, breeding system, the abundance and genetic diversity of the original populations, distance between remnants, possible gene flow mechanisms (pollen and seed), and interactions with pollinators and dispersal vectors (Hamrick 1994, Young et al. 1996).

Few studies have demonstrated direct genetic effects of forest fragmentation, which requires either sufficient sites to infer change, or longitudinal sampling across time (e.g. Prober and Brown 1994). However, various studies have shown changed reproductive success in small populations of plants in fragmented habitats in Australia (**Table 3**), a potential precursor to altered genetic diversity.

The rare species *Eucalyptus benthamii* occurs in country that has been extensively cleared of forest. Microsatellite markers revealed significant divergence among all four remnant populations, despite two being separated by only a few kilometres (Butcher et al. 2005). However, since the trees are 35-200 years old, genetic divergence between populations may have occurred prior to land clearing. Fragmentation and tree isolation appears to have resulted in higher levels of selfing and biparental inbreeding in some remnants. There was also evidence that interspecies gene flow (producing hybrid progeny) increased with fragmentation. Seed viability and germination rates were low in the remnant populations.

Rossetto et al. (2004) sampled the widespread, early successional rainforest tree *Elaeocarpus grandis* across the southern range of the species to compare the genetic characteristics of undisturbed and fragmented populations. Overall levels of diversity were higher than in closely related endemic species, but lower than those in non-Australian rainforest trees. No significant genetic structure was detected, which may be a consequence of efficient pollen or seed dispersal mechanisms. Larger *E. grandis* populations tended to contain greater allelic diversity, while more isolated populations had decreased heterozygosity and higher inbreeding. Effects were greater within the extensively cleared Big Scrub group of populations. The authors suggested that lowland 'expansion' areas (such as the Big Scrub) had previously facilitated genetic exchange and led to increases in population size during inter-glacial periods.

Table 3 Example Australian studies on genetic effects of habitat fragmentation on forest species

Species	Fragmentation effects	Type of study	Reference
Acacia dealbata	Low seed set, limited recruitment, aging stands	Fertilisation success, reproductive output of 11 fragmented populations over 2 years	Broadhurst and Young 2006
Acacia dealbata	Mate limitation in small populations (self-incompatibility mechanisms)	Genetic diversity, mating system, and progeny growth parameters of the seed crops	Broadhurst et al. 2008b
Four *Austromyrtus* species including *A. gonoclada* (rare species)	Rarest species had higher genetic diversity (less time since isolation?) but very few seedlings and low germinability	Genetic variability, stand structure, and reproductive activity	Shapcott and Playford 1996
Castanospermum australe	Reduced seed predation, increased seedling establishment and sapling survival in smaller rainforest remnants	Field ecology – seed fate and vegetation survey in rainforest remnants	Lott 1997
Elaeocarpus grandis	Increased inbreeding in rainforest fragments. No significant genetic population structure, suggesting dispersal and colonisation mechanisms maintain gene flow	Medium term (over 100 years) effects of rainforest fragmentation – five microsatellite loci	Rossetto et al. 2004
Eucalyptus albens	Lower diversity in populations less than 500 individuals, except where <250 m from larger stands (populations)	Genetic diversity (allozyme electrophoresis)	Prober and Brown 1994
Eucalyptus benthamii	Increased inbreeding and interspecies gene flow in remnant populations	Genetic analysis (microsatellite markers) and seedling morphology	Butcher et al. 2005

Despite their smaller population size, forest remnants are important sources of population genetic diversity (see **Chapter 9**). Byrne et al. (2008) found pollen dispersal over 1 kilometre between remnant populations of *Eucalyptus wandoo* in south-west Western Australia, highlighting the role of remnant patches in maintaining genetic connectivity at the landscape scale.

5.6.2 Inbreeding depression

Inbreeding can occur when plants self-pollinate or mate with relatives, and can result in the accumulation and expression of deleterious alleles. Inbreeding depression may limit local adaptation in wild populations (Willi et al. 2006), as well as the response to artificial selection in breeding programs (Kardos et al. 2016, Nickolas et al. 2019).

Inbreeding is a potential consequence of one or more of habitat fragmentation, loss of pollinators, production of smaller flowers, or reduced population sizes (Nickolas et al. 2019). It may also be a consequence of climate change when there is an interplay between maladaptation, range fragmentation or range shifts (Lenoir et al. 2008) and founder effects at the trailing and leading edge of a species range (Hampe and Petit 2005, Leimu et al. 2010).

A 28-year study of open-pollinated and self-pollinated *Eucalyptus globulus* and *E. ovata* individuals documented reduced early growth and lower long-term survival in selfed individuals (Nickolas et al. 2019). Very few selfs survived to reproductive maturity compared with outcrosses.

5.6.3 Gene flow from plantations

Gene flow from plantations can alter the genetic make-up of local populations of native trees through introgression, defined as the infiltration of genes from one species or provenance into another through hybridisation (Potts et al. 2001; Larcombe et al. 2016).

A number of native forest eucalypt species have been identified as susceptible to hybridisation with shining gum (*E. nitens*) or southern (Tasmanian) blue gum (*E. globulus*) in nearby plantations (Forest Practices Authority 2009; Barbour et al. 2010). A similar situation exists for native forest spotted gum (*C. citriodora* subsp. *variegata*) and plantation cadaghi (*C. torelliana*) (Wallace and Leonhardt 2015; Shepherd and Lee 2016), and native forest Queensland western white gum (*E. argophloia*) and a variety of plantation species (Randall et al. 2016). In the case of *Corymbia*, some first-generation (F1) crosses are present in the native stands, but not many second-generation crosses (Wallace and Leonhardt 2015; Shepherd and Lee 2016). Remnant native populations of *Eucalyptus loxophleba* are also susceptible to hybridisation with conspecifics in nearby plantations (Sampson and Byrne 2008).

Pollination contamination is a particular concern for remnant macadamia populations, which are rare and endangered in their native habitat, with genetic threats of inbreeding among populations and loss of fertility due to isolation and habitat fragmentation (Powell et al. 2014). Hybridisation with horticultural cultivars can lead to gene flow from macadamia plantations to remnant rainforest trees (O'Connor et al. 2015), and less than 4% of wild *Macadamia tetraphylla* populations are isolated from the potential to cross with commercial cultivars (see Macadamia Case Study, **Chapter 7**).

Gene flow can be managed through careful location and management of plantations, to conserve wild genetic stock. Tasmania has guidelines to reduce the risk of genetic contamination of native stands, particularly where the susceptible species are of high conservation value, through risk assessment, regular monitoring for flowering and hybrid seedlings, and careful decisions regarding replanting of plantations (Forest Practices Authority 2009). Other strategies include careful selection of species and provenances; manipulation of flowering times and flower abundance; and silvicultural practices such as isolation, the use of buffer zones of non-interbreeding species, and closer planting to reduce the area of crowns able to produce flowers (MIG and NFISC 2018).

5.6.4 Seed collections for restoration plantings

When revegetation is used to restore habitat, it is important to consider the collection quantity, frequency and location for seed used to establish plantings. Revegetation projects (Byrne et al. 2011) can result in species and provenances being planted outside their natural range, which can affect local genetic diversity. Consideration of choice of provenance can reduce the impact of gene flow from planted trees to nearby native vegetation. However, there is often a shortage of seed for revegetation and restoration plantings (Broadhurst et al. 2008a, 2021), and this can limit not only which species are planted, but the source and genetic diversity of the seed. It is also important to collect from widely separated trees (which are more likely to be genetically distinct), and not to overharvest source trees.

5.6.5 Climate adaptation

Climate change is predicted to lead to changes in temperature and rainfall, and increased frequency and intensity of both drought and fire. Species will likely change in genetic diversity and distribution as they respond and adapt to climate change. Management of forest genetic resources under climate change is covered in **Chapter 10**.

5.7 Needs, challenges and opportunities

Patterns and trends in genetic diversity are useful to inform seed collection, genetic sampling, tree breeding strategies, and landscape-scale conservation. Low genetic diversity of remnant populations is of concern for species conservation, and domestication programs require maximal genetic diversity to facilitate efficient selective breeding and genetic improvement of commercially significant species.

However, the genetic diversity of a species cannot be predicted simply from its range size, growth form, abundance, biome, or historic or current isolation. Species-specific management requires knowledge of the genetic characteristics and breeding system of that particular species. As outlined above, the effects of historical, current and future factors affecting genetic diversity in forest species are complex, and differ between species.

Similarly, while it can be assumed that genetic changes will occur as a result of forest fragmentation, the nature of those changes cannot always be predicted (Young et al. 1996). Ultimately, empirical investigations across representative taxa and within suitable study systems are required to demonstrate changes in population dynamics caused by fragmentation of natural ecosystems (Rossetto et al. 2004).

The number of Australian forest species for which molecular data on genetic structure or variation is available is still very small compared to the total number of forest species, although understanding is increasing. Only a small number of threatened species have been investigated (Broadhurst et al. 2017), and further work is required on some of the more common eucalypt and acacia species.

Conservation strategies have generally been based on the assumption that broad management measures will ensure conservation of species genetic diversity. However, there is increasing recognition that understanding genetic diversity is a specific part of management, particularly with respect to the effects of climate change and other key threats. Australia's Threatened Species Strategy 2021-31[27] includes development of actions to address genetic diversity issues, including the potential accelerated use of genomics and population genetics to inform management of target species (see also **Chapter 10**).

There are several constraints on raising the awareness of the value and importance of forest genetic diversity. The primary ones are:

- that scientific work on genetic diversity is often highly technical
- that genetic diversity information is rarely integrated into public communication and conservation measures
- the lack of public and political understanding of the importance of forest genetic diversity for conservation and human use.

[27] awe.gov.au/environment/biodiversity/threatened/publications/strategy-home

5.8 Priorities for capacity-building and research

The priorities for capacity-building in forest genetic diversity are:

- training for scientists in genetics
- funding for ongoing research in forest genetics
- improved communication about the importance of within-species genetic diversity for conservation and future human use.

The priorities for research in forest genetic diversity are:

- inclusion of Australian forest tree and woody plant species of human significance in national and international database projects
- characterising priority species using a combination of field and genetic studies (e.g. Butcher et al. 2005, Rossetto et al. 2017)
- investigating changes in genetic diversity over time, such as longitudinal studies that compare existing seed collections and herbarium specimens with current in situ material
- monitoring changes over time in genetic diversity of priority species in response to key threats and threat combinations (e.g. Rossetto et al. 2004)
- landscape-scale conservation measures that protect populations and species, and identifying climate refugia
- incorporating climate change predictions into revegetation and tree breeding programs through provenance and seed source selection, translocation and assisted gene flow.

6 In situ conservation of forest genetic resources

6.1 Key points

- Australia's *National Forest Policy Statement* commits the Australian, state and territory governments to maintain an extensive and permanent native forest estate, and to manage native forest in an ecologically sustainable manner.
- As at 2016, 33.6 million hectares (25%) of Australia's forests, including a range of forest species and ecological communities, were in the National Reserve System.
    - The National Reserve System is managed through the collective efforts of the Australian Government, state and territory governments, and Indigenous and private landholders and non-government organisations.
- Regional Forest Agreements (RFAs) are a key element of Australia's forest management in four Australian states. At signing of the RFAs, Australia established a CAR reserve system based on principles of Comprehensiveness, Adequacy and Representativeness.
    - The four components of the CAR reserve system are formal reserves on public land (protected by legislation), informal reserves on public land (protected through administrative instruments), public land managed by prescription under regulated management plans, and complementary arrangements on private land.
    - As at 2020, the CAR reserve system in RFA regions across all tenures contained 10.0 million hectares of native forest ecosystems.
- Other areas managed for protection of biodiversity are in the Defence estate, World Heritage areas, sites on the Ramsar List of Wetlands of International Importance, multiple-use forests (which are managed for a range of values, including biodiversity), other forests on nature conservation reserve tenure, and private covenanted land.
- When all these mechanisms are considered together, as at June 2016 a total of 46.0 million hectares (35%) of Australia's native forest was managed for the protection of biodiversity through formal and informal processes.
    - This is the area of forest that provides in situ conservation of forest genetic resources.
- Australia's legal system includes measures to assess, list and manage species that are deemed to be threatened.
    - As at December 2020, recovery plans are in place for 8 of the 17 species on the FAO list of forest genetic resources for Australia that are listed as threatened under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*.
- Needs, challenges and opportunities for improving in situ conservation of forest genetic resources include:
    - increased control of invasive species and feral animals
    - better understanding and managing fire regimes, including through use of traditional Indigenous burning techniques
    - countering the direct and indirect effects of climate change, including through developing corridors between protected areas
    - more knowledge of genetic diversity and adaptability of key forest genetic resources, to inform their conservation and management.

6.2 Australia's forest policy for conservation

In situ conservation is the preferred means of conserving forest genetic resources, as it allows forest trees and other woody plant species to continue their evolutionary processes and adaptation to changes (FAO 2014b).

Australia's management and conservation of forests is underpinned by the *National Forest Policy Statement*[28] (NFPS), which was jointly developed by the Australian, state and territory Governments.

The NFPS commits these governments to maintain an extensive and permanent native forest estate, and to manage the native forest estate in an ecologically sustainable manner for current and future generations, including to conserve biological diversity, heritage, Indigenous and other cultural values. The commitment to sustainable management of all Australian forests applies whether the forest is on public or private land, or is reserved or available for production.

The NFPS sets out broad national goals to be pursued at regional levels. Its framework integrates environmental, social and economic objectives. The role of the Australian Government is to coordinate a national approach to environmental and industry-development issues, while state and territory governments have responsibility for land management.

The NFPS led to the creation of a comprehensive, adequate and representative (CAR) reserve system, developed through consideration of areas required to maintain viable populations and genetic diversity, the need for replication of protected communities, the protection of rare, vulnerable and endangered species, and the protection of old-growth forest and wilderness areas. The CAR reserve system is built on nationally agreed criteria (Commonwealth of Australia 1997), forms the scientific framework for the National Reserve System[29], and applies throughout Australia for both terrestrial and marine areas at Australian, state and territory levels. The CAR principles were applied when developing, implementing and reviewing Australia's Regional Forest Agreements (RFAs), and the CAR reserve system in RFA regions was implemented at the signing of the RFAs.

There are four components of the CAR reserve system:

- Public land
    - dedicated (formal) reserves that can only be revoked with parliamentary approval
    - informal reserves protected by public authorities through administrative instruments
    - forests managed by prescription or management plans.
- Private land
    - private reserves under long-term secure arrangements such as proclamation under legislation, or contractual arrangements such as covenants.

[28] awe.gov.au/agriculture-land/forestry/policies/forest-policy-statement
[29] awe.gov.au/agriculture-land/land/nrs/science/scientific-framework

6.3 Mechanisms for in situ conservation of forest genetic resources

6.3.1 Regional forest agreement regions

Regional Forest Agreements are a key element of Australia’s forest management. Ten RFAs across four states cover the main commercial native forestry regions. The RFAs are long-term plans for the sustainable management and conservation of Australia’s forests in areas intensively managed for timber production, that balance the full range of environmental, social, economic and heritage values that forests can provide for current and future generations (Davey 2018a). Each aspect of forest management addressed by RFAs relates to the sustainable use and conservation of forest genetic resources: resource access and supply to industry, ecologically sustainable forest management, and a permanent forest conservation estate.

One of the key achievements of the RFAs was the establishment of a CAR reserve system, based on nationally agreed criteria known as the ‘JANIS’ criteria (Commonwealth of Australia 1997), covering biodiversity, old-growth forests and wilderness. The CAR reserve system is based on three principles:

- including the full range of vegetation communities (comprehensive)
- ensuring a sufficient level of reservation to maintain species diversity (adequate)
- conserving the diversity within each vegetation community, including genetic diversity (representative).

The CAR reserve system established at signing the RFAs was science-based, deriving from Comprehensive Regional Assessments of forest values and uses (Davey et al. 2002; Davey 2018a) and consultation with stakeholders.

All four components of the CAR reserve system are represented within RFA regions:

- dedicated formal reserves on public land
- informal reserves on public land, such as special protection zones in State forests
- areas managed by prescription on public land, such as forests managed under codes of practice or management plans, riparian vegetation, steep slopes, or other areas with rare, dispersed or unmappable values
- areas on private land managed under secure arrangements, such as conservation covenants.

6.3.2 National Reserve System

Australia’s National Reserve System[30] is Australia's formal network of protected areas, conserving examples of natural landscapes and native plants and animals, and thus contributing to the in situ conservation of forest genetic resources. It includes Commonwealth, state and territory reserves, as well as Indigenous lands, and protected areas run by non-profit conservation organisations. The National Reserve System is underpinned by the CAR reserve system criteria[31], and is guided by the Strategy for Australia's National Reserve System 2009-2030[32].

[30] awe.gov.au/agriculture-land/land/nrs
[31] awe.gov.au/agriculture-land/land/nrs/science/scientific-framework
[32] awe.gov.au/agriculture-land/land/nrs/publications/strategy-national-reserve-system

6.3.3 Multiple-use public native forests

Multiple-use public native forests are public state forest, timber reserves and other forest areas, and are managed for a range of forest values, including wood harvesting, water supply, biodiversity conservation, recreation and environmental protection. They occur both within and outside RFA regions.

State and territory governments of Australia are responsible for management of multiple-use public native forests. Management codes and guidelines protect the biodiversity within multiple-use public forests, including their genetic resources.

Management plans and/or harvest permits are required for species harvested from native forests.

6.3.4 Private land

Some private land is subject to voluntary legal conservation agreements, through which a landowner signs a perpetual conservation covenant agreeing to protect a part of their property that will remain protected even if the land is sold. The landowner can continue to manage the rest of their land for production, and can receive help from the covenanting organisation to manage their protected area.

6.4 Extent of forest conservation

A total of 33.6 million hectares of Australia's forest is protected in the National Reserve System as at 2016 (MIG and NFISC 2018). This is 25% of Australia's forest area.

Inclusion of an area in Australia's National Reserve System reflects the management intent of that area rather than the underlying land tenure. Forest on nature conservation reserve tenure comprises 21.0 million hectares (62%) of the forest in the National Reserve System, with substantial contributions to the National Reserve System also from forest on private (23%) and leasehold (11%) tenures (MIG and NFISC 2018). Some large national parks, including Kakadu National Park in the Northern Territory, are classified as private land tenure but are included in the National Reserve System because they are formally managed for conservation values.

The National Reserve System includes 12 mainland World Heritage areas protected under World Heritage Convention arrangements. A total of 4.7 million hectares of forest was in Australia's World Heritage Areas as at 2016 (MIG and NFISC 2018). Forested World Heritage areas in Australia include Kakadu National Park (Northern Territory), the Wet Tropics of Queensland, Shark Bay (Western Australia), Fraser Island (Queensland), Gondwana Rainforests (New South Wales), the Greater Blue Mountains Area (New South Wales), and the Tasmanian Wilderness World Heritage Area.

The CAR reserve system created in RFA regions at signing of the RFAs (1997-2001) contained 8.4 million hectares of native forest ecosystems. Significant areas of forest were included to meet reservation thresholds (Davey 2018a), including the conservation of the genetic resources of some key forestry species. Further reservation since signing the RFAs has led to the CAR reserve system in RFA regions containing 10.0 million hectares of native forest ecosystems, including 3.6 million hectares of old-growth forest (Jacobsen et al. 2020a).

Other mechanisms used in Australia for forest conservation, and which contribute to the in situ conservation of forest genetic resources, are areas under private covenant (0.15 million hectares of forest), multiple-use forests (9.6 million hectares of forest), protected areas in the Defence estate (1.3 million hectares of forest), and sites on the Ramsar List of Wetlands of International

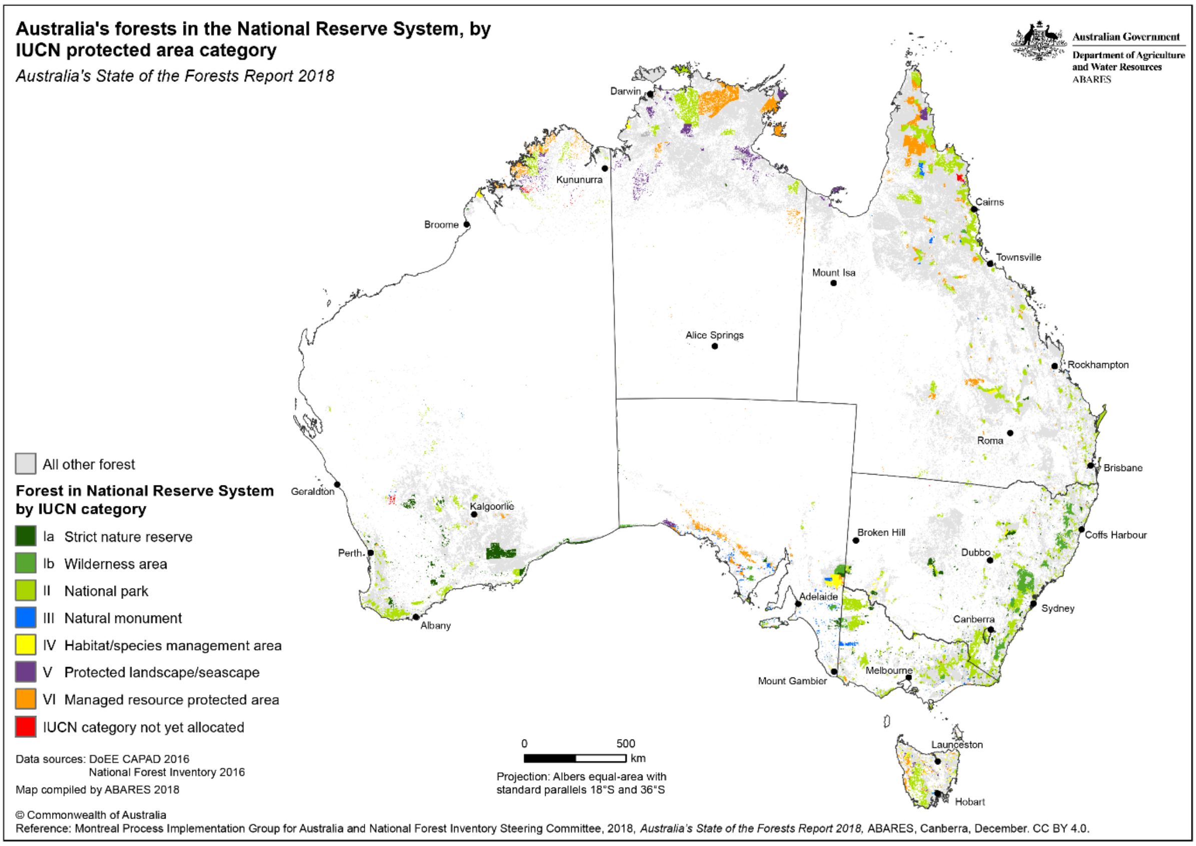
Importance (1.8 million hectares), as well as other forests on nature conservation reserve tenure (MIG and NFISC 2018). When all these mechanisms are brought together, as at June 2016 a total of 46.0 million hectares of Australia's native forest is managed for the protection of biodiversity through formal and informal processes (MIG and NFISC 2018). This is 35% of Australia's native forest area, and is the area of forest that provides in situ conservation of forest genetic resources.

6.4.1 National Reserve System by IUCN protected area category

Land and forest in Australia's National Reserve System can be classified into categories created by the International Union for Conservation of Nature (IUCN).

The 33.6 million hectares of Australia's forests in dedicated formal conservation reserves are shown by their IUCN category on **Map 1**. Of Australia's national forest types, all but one have reservation levels that exceed the 10% threshold recommended by IUCN; only acacia forests are below this target, with 9.6% of their area reserved (MIG and NFISC 2018).

Map 1 Forest in Australia's National Reserve System by IUCN reserve category



Source: *Australia's State of the Forests Report 2018*, Figure 1.16. Map available at awe.gov.au/abares/forestsaustralia/sofr/sofr-2018/maps#criterion-1-maps-and-other-graphics.

6.4.2 Targeted species conservation

In situ conservation programs can consider individual species in two ways: either as part of declaring a reserved area (a priori), or under the threatened species program (a posteriori). The data in **Appendix A** give the species known to have been considered for in situ conservation in either of these ways. However, national data on the location, number and area of genetic conservation units that have been established specifically for in situ conservation of targeted species, or are being managed specifically for in situ conservation of targeted species, have not been compiled.

Wollemia nobilis, Eucalyptus ovata, E. morrisbyi and *Callitris oblonga* are examples of forest tree species that have been conserved in situ for genetic conservation reasons (Singh et al. 2013). The conservation of a representative genetic range of some key forestry species, for example *Acacia mangium* and *Araucaria cunninghamii*, was also implemented in the RFA process and other reservation processes. Some reserves have been declared or extended, at least in part, because they contain a representative population of a rare or significant species: examples include *Backhousia subargentea* and *Macadamia integrifolia* (Amamoor National Park, south-east Queensland[33]), and *Eucalyptus camaldulensis* and *Acacia carneorum* (Kinchega National Park, New South Wales[34]).

Mount Bauple National Park in eastern Queensland protects the wild genetic stock of *Macadamia integrifolia* from which the macadamia nut industry was developed (DES 2020). This species grows in vine forests threatened by land clearing and fragmentation, and research is being undertaken to prevent its further decline and to protect its genetic integrity.

Australia's conservation system also includes measures to manage individual species that are assessed and listed as threatened under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Of the 129 forest species and hybrids currently listed as forest genetic resources for Australia by the FAO, 17 species or subordinate taxa (13%) are listed as threatened under the EPBC Act. Of these, 11 species, subspecies or varieties are listed as vulnerable, nine as endangered, and two (*Acacia cochlocarpa* subsp*. velutinosa* and *Wollemia nobilis*) as critically endangered (the total sums to more than 17 as for some species more than one subspecies is listed separately under the EPBC Act). Included in the list are the two main commercial *Macadamia* species (*M. integrifolia* and *M. tetraphylla*), which are listed as vulnerable in their natural habitat due to land clearing and small population size.

Recovery plans exist for eight of the threatened species on the FAO list of forest genetic resources for Australia: *Acacia cochlocarpa, Callitris oblonga, Eucalyptus crenulata, E. burdettiana, E. morrisbyi, Macadamia integrifolia, M. tetraphylla* and *Wollemia nobilis*. These species have total known populations of approximately 135-6000 wild individuals[35].

6.5 Programs for in situ conservation of forest genetic resources

Through the National Reserve System Program (1996-2013), the Australian Government provided approximately $200 million in funding to assist the purchase of 371 properties (around 10 million hectares) for addition to the National Reserve System[36].

Between 2008 and 2013, through the Caring for our Country program, the Australian government provided financial assistance to encourage private applicants to establish and/or purchase land as a protected area to be managed as part of the National Reserve System in perpetuity. The successful applicants were required to prepare a plan of management and follow specified guidelines and process for conservation management. The initiative particularly focused on the remaining bioregions with very low levels of protection, and areas of global

[33] npsr.qld.gov.au/managing/plans-strategies/statements/amamoor.html
[34] environment.nsw.gov.au/research-and-publications/publications-search/kinchega-national-park-conservation-management-and-cultural-tourism-plan
[35] awe.gov.au/environment/biodiversity/threatened/recovery-plans
[36] awe.gov.au/agriculture-land/land/nrs

conservation significance, including the world's largest relatively intact subtropical savannah which stretches across Australia's north from Cape York to the Kimberley.

A number of non-government organisations such as Bush Heritage Australia and the Australian Wildlife Conservancy also have biodiversity conservation programs.

6.6 Needs, challenges and opportunities

Needs, challenges and opportunities for improving in situ conservation of forest genetic resources include:

- increased control of invasive species and feral animals
- better understanding and managing fire regimes, including through use of traditional Indigenous burning techniques
- countering the direct and indirect effects of climate change, which are predicted to include reduced rainfall in southern Australia and more intense and frequent bushfires, and hotter and wetter conditions in northern Australia. A recent modelling analysis concluded that existing National Reserve System boundaries will not necessarily protect present-day ecological environments under future climate change scenarios (Williams et al. 2016). It will therefore be important to develop connections between protected areas to facilitate species movement.
- more knowledge of genetic diversity and adaptability of key forest genetic resources, to inform their conservation and management.

6.7 Priorities for capacity-building and research

The key priorities for capacity-building and research to support in situ conservation of forest genetic resources include:

- protecting forests from incursions of pests and diseases (e.g. myrtle rust), and the changing impact of pests and diseases as a result of climate change
- protecting against increasing development pressures on forests, such as urbanisation, agricultural expansion, mining and extractive industries, and tourism
- increasing the ability for active management of protected areas, so as to retain their full range of biodiversity and natural values under environmental stress
- further understanding and managing the effect of climate change on forests, including effects on gene diversity and flow, and implementing management to help species to adapt to, and survive, climate change.

7 Ex situ conservation of forest genetic resources

7.1 Key points

- The mechanisms used for ex situ conservation of Australian forest species are seed banks (in Australia and overseas), provenance or clonal plantings, seed orchards, seed production areas, and conservation plantings (living collections, conservation stands, translocated plantings, and biodiverse revegetation plantings).
- There is ongoing management of ex situ genetic material collections, seed orchards and conservation stands for the major commercial forestry species, as well as for *Macadamia integrifolia* (macadamia) and *Melaleuca alternifolia* (tea tree).
  - *Macadamia integrifolia* is conserved ex situ as part of both tree breeding and threatened species recovery programs.
  - However, for other forest species of interest, ex situ conservation is limited to seed collections or provenance trials, and most forest species are not conserved ex situ.
- Of the 129 species and hybrids listed by FAO as forest genetic resource for Australia, 127 have seed in a seedbank, and 50 have at least one other mechanism of ex situ conservation in Australia.
- Biodiverse restoration plantings for which the provenance of the genetic material is recorded are increasingly contributing to ex situ conservation.
- Separate national or sub-national agencies are responsible for different aspects of ex situ conservation of forest genetic resources:
  - The main seed banks in Australia for forest tree species are managed by the Australian Tree Seed Centre (ATSC), SeedEnergy, and some state forestry agencies.
  - The main conservation seed banks for threatened and some other forest species are managed by the Australian Seed Bank Partnership (ASBP, a collaborative partnership between Australian, state, territory and local governments), and by Greening Australia (Nindethana Australian Seeds).
  - The Millenium Seed Bank at the Royal Botanic Gardens, Kew (United Kingdom), also holds seed from a large number of Australian species, including some forest species.
- Challenges to ex situ conservation in Australia include variable seed production; species with seeds with poor storage ability; drought; bushfire; land-use change; long distances between native species habitat and infrastructure; and decreased investment in tree breeding.
- Opportunities exist for increased ex situ conservation through the Australian Seed Bank Partnership and other seed bank facilities, and through encouraging community participation in organised seed collection.
  - Designation and management of seed production areas could supplement collection of seed from native stands, and be more sustainable.
- Priorities for capacity-building and research include conservation of a wider range of species ex situ, improved documentation of seed provenance, and regular seed viability testing, as well as provenance trials to investigate the climate-change tolerance of key species, and establishment of ex situ conservation sites in areas predicted to be suitable in future climates.

7.2 State of ex situ conservation in Australia

Ex situ conservation is a necessary complement to in situ conservation (see **Chapter 6**), especially when population size is critically low in the wild (FAO 2014b). Ex situ conservation also allows genetic resources for current or future human use to be captured and managed.

Australia has ex situ conservation programs for commercial plantation species used for wood or oil production, or for macadamia nuts, as well as for a small number of threatened species. The mechanisms used for ex situ conservation are seed banks (Australia and overseas), provenance or clonal plantings, seed orchards, seed production areas, and conservation plantings including seed stands, translocations and biodiverse revegetation plantings.

For the major forestry plantation species, as well as *Macadamia integrifolia* (macadamia) and *Melaleuca alternifolia* (tea tree), there is ongoing management of ex situ genetic material collections, seed orchards and conservation stands. However, for other forest species of interest, ex situ conservation is limited to seed collections or provenance trials, and most other forest species are not conserved ex situ.

Of the 129 species and hybrids listed by the FAO as forest genetic resource for Australia, 127 have seed held in a seedbank (the exceptions are *Syzygium luehmannii* and *Fontainea picrosperma*), and 50 have at least one other mechanism of ex situ conservation in Australia.

7.3 Mechanisms for ex situ conservation in Australia

Separate national or sub-national agencies are responsible for different aspects of ex situ conservation of forest genetic resources, with different organisations responsible for breeding of native and pine tree species, for seed collection, and for threatened species management. Information exchange between organisations with different ex situ conservation responsibilities occurs on an ad hoc basis.

7.3.1 Seed banks

Seed banks are an important mechanism for safe and efficient storage of both wild and improved plant genetic material. For the majority of species listed by the FAO as forest genetic resources for Australia, storage of seed in a seed bank is the only ex situ conservation mechanism.

Operation of seed banks requires sound understanding of seed harvest, storage and germination requirements. For those species for which seed can be dried and stored, seed banks prolong seed viability and maximise its availability for future research and planting (ASPB 2016).

The main seed banks in Australia are managed by:

- Australian Tree Seed Centre (ATSC), SeedEnergy and some state forestry agencies, for forest tree species
- Australian Seed Bank Partnership (ASBP), and Greening Australia (Nindethana Australian Seeds), for threatened and some other forest species. The ASBP is a national, collaborative partnership between Australian, state, territory and local governments through botanic gardens and state agencies.

These organisations aim to collect seed using methods that meet the criteria for a conservation collection. Most seed collections in Australia are made from native stands under a permit system (**Chapter 8**). For plantation species, seed can be wild-collected, or improved through selection (**Table 4**). Seed collections within seed banks are not generally based on molecular information.

Table 4 Native plantation species with reproductive material in seed collections in Australia

Species	Type of seed material [a, b]	Notes
Acacia auriculiformis	improved	This table presents only key forestry plantation species, and does not include many other species collected for genetic conservation, research, revegetation or international purposes, or seed collected for prompt use by some forestry and revegetation organisations without long-term storage. [a] Seed available as at December 2020. Seed collections listed here are made from representative or high-quality trees from known provenances or parents, and are stored in facilities under controlled conditions to maximise seed longevity. [b] Wild seed collections are from selected provenances. For species with improved seed, wild seed is also available. Source: organisations listed in **Table 7** as well as the Australian Seed Bank Partnership; Nindethana Australian Seeds; Northern Territory Department of Industry, Tourism and Trade; University of Tasmania; VicForests; Victorian Department of Environment, Land, Water and Planning; and Western Australian Department of Biodiversity, Conservation and Attractions.
A. crassicarpa	improved	
A. mangium	improved	
A. melanoxylon	improved	
Acacia other species	wild	
Araucaria cunninghamii	improved	
Casuarina cunninghamiana	wild	
C. obesa	wild	
Casuarina various species	improved	
Corymbia citriodora subsp. *citriodora*	improved	
C. citriodora subsp. *variegata*	improved	
C. henryi	improved	
C. maculata	improved	
C. torelliana	cultivated	
Eucalyptus argophloia	improved	
E. astringens	wild	
E. benthamii	improved	
E. botryoides	improved	
E. camaldulensis subsp. *simulata*	improved	
E. camaldulensis var. *camaldulensis*	improved	
E. camaldulensis var. *obtusa*	improved	
E. cladocalyx	improved	
E. cloeziana	improved	
E. dunnii	improved	
E. globulus	improved	
E. grandis	improved	
E. kochii	wild	
E. leucoxylon	wild	
E. longirostrata	wild	
E. moluccana	wild	
E. nitens	improved	
E. occidentalis	improved	
E. pellita	improved	
E. pilularis	improved	
E. polybractea	improved	
E. punctata	wild	
E. saligna	improved	
E. sieberi	improved	
E. sideroxylon	wild	
E. smithii	improved	
E. tereticornis subsp. *tereticornis*	improved	
E. tricarpa	improved	
E. viminalis	wild	
Eucalyptus other species	wild	
Grevillea robusta	improved	
Santalum album	wild, cultivated, improved	
S. lanceolatum	improved	
S. spicatum	wild	

Australian Tree Seed Centre

The main forest tree seed program is implemented by the Australian Tree Seed Centre (ATSC) based at CSIRO, which has collected, stored and distributed seed from forest tree species of economic and social importance in Australia and overseas for over 60 years. The ATSC also participates in research and collaborative work on forestry tree species.

The ATSC maintains a national collection of seeds of more than 770 tree and shrub species in some 78 genera, including as at November 2020 more than 230 *Acacia*, 17 *Allocasuarina*, 10 *Casuarina*, 24 *Corymbia*, 295 *Eucalyptus* and 36 *Melaleuca* species. Separate collections are also held for subspecies of a range of eucalypt species. As at December 2020, the ATSC has seed collections for 90 of the taxa listed by FAO as forest genetic resources for Australia.

Generally, the ATSC collects seed by provenance (locality). Where possible, a provenance collection comprises the seed of 10 or more mother trees spaced sufficiently far apart to avoid collecting from close relatives. Some collections from mother trees are maintained as separate individual collections, and some are bulked together. For key species that are likely to be of interest for domestication or scientific studies, a wide range of provenances is collected.

For example, in 1987 and 1988, with increasing worldwide interest in breeding *Eucalyptus globulus* for pulpwood plantations, ATSC undertook the largest native stand seed collection of *E. globulus* and intergrade populations (Potts et al. 2014). This collection was funded by Australian and overseas forestry companies, and comprised 616 parent trees from 49 collecting localities (see also Gardiner and Crawford 1987; Jordan et al. 1993; Dutkowski and Potts 1999).

Australian Seed Bank Partnership

The Australian Seed Bank Partnership (ASBP) is a national collaboration among 15 partners and associates (see **Table 5** and **Map 2**), which aims to conserve Australia's native plant diversity through collaborative and sustainable seed collecting, banking, research and knowledge-sharing. Individual partners in the ASBP have collection records available, and Australian Seed Bank online[37] (hosted through the Atlas of Living Australia) displays and maintains all ASBP records.

Seed banks throughout Australia (**Map 2**) maintain various levels of seed storage capabilities, including cryopreservation storage facilities. The ASBP undertakes regular audits of the facilities of its partner seed banks to better inform strategic research and ex situ conservation efforts.

As at October 2021, across its partners ASBP has at least one collection for 110 of the species and hybrids listed by FAO as forest genetic resources for Australia. The seed collection at the Australian National Botanic Gardens currently includes 44 species on the FAO list of forest genetic resources for Australia.

ASBP partners coordinate collection of plant seed, including for threatened species. The ASBP aims to collect at least 20,000 seeds for each taxon, the generally accepted necessary size for a conservation collection. Viability testing typically occurs at 5-yearly intervals, and seed is made available for research or vegetation restoration.

The ASBP has worked to increase banking of seed from threatened species, including from species susceptible to myrtle rust, or experiencing habitat loss as a result of the extensive 2019-20 fire season in south-eastern Australia. These collections may be used in future to

[37] asbp.ala.org.au/

strengthen or re-establish populations at threat or where localised extinction has occurred (ASBP 2016).

Table 5 Partners and associates in the Australian Seed Bank Partnership (as at October 2021)

Alice Springs Desert Park, Parks and Wildlife Commission of the Northern Territory
Australian Network for Plant Conservation
Australian Grains Genebank
The Australian PlantBank, The Australian Botanic Garden, Mt Annan, The Royal Botanic Gardens and Domain Trust
Brisbane Botanic Gardens, Mt Coot-tha, Brisbane City Council
Greening Australia
George Brown Darwin Botanic Gardens, Parks and Wildlife Commission of the Northern Territory
Millennium Seed Bank Partnership, Royal Botanic Gardens, Kew, United Kingdom
The National Seed Bank, Australian National Botanic Gardens, Australian Capital Territory
South Australian Seed Conservation Centre, Botanic Gardens and State Herbarium, South Australia
Tasmanian Seed Conservation Centre, Royal Tasmanian Botanical Gardens
The Queensland Herbarium
The Victorian Conservation Seedbank, Royal Botanic Gardens Victoria
The Western Australian Seed Centre, Kings Park, Botanic Gardens and Parks Authority
The Western Australian Seed Centre, Kensington, Department of Biodiversity, Conservation and Attractions

Source: seedpartnership.org.au/

As at June 2020, 68% of Australia's listed threatened plant species have been conserved in seed banks[38]. For example, the Australian PlantBank, opened in 2013 at the Australian Botanic Garden, Mount Annan, New South Wales, maintains over 10,000 seed collections, as an insurance policy against extinction of native plants in the wild. In addition to its seed vault, the Australian PlantBank has tissue culture or cryopreservation storage facilities for species that cannot be stored as seed. As at June 2019, the PlantBank held 5,156 Australian species as seed collections, and 35 species as tissue culture collections, including over 50% of the listed threatened species in New South Wales[39].

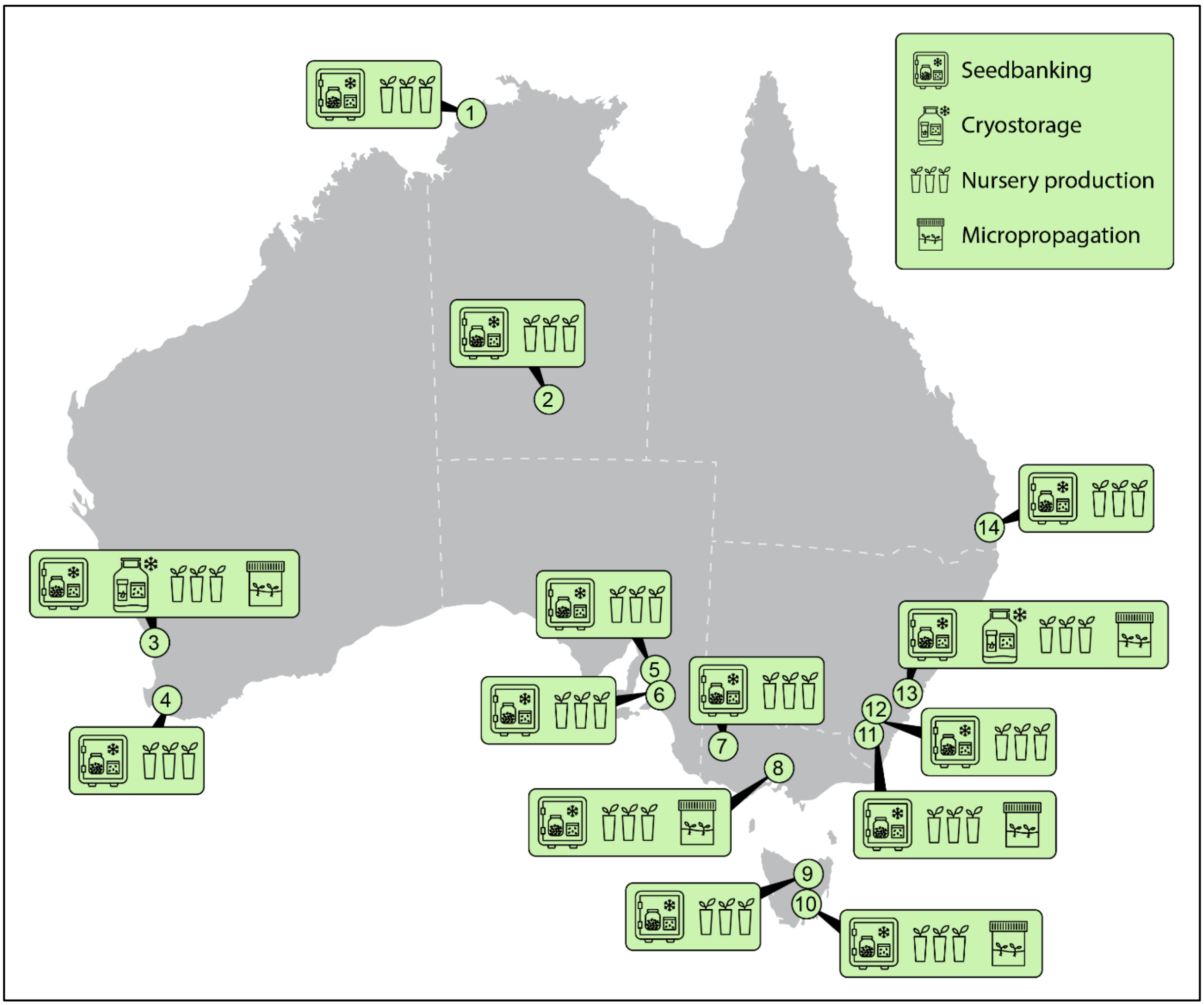
Through the ASBP, Australia is a partner in the Millennium Seed Bank Partnership, the largest ex situ conservation project in the world, run by the Royal Botanic Gardens, Kew[40]. Australia has 12,300 seed collections across 9,000 taxa in the Millennium Seed Bank, forming the largest component of collections from countries outside the United Kingdom. The ASBP is also contributing to the Millennium Seed Bank Partnership's Global Tree Seed Bank Project (GTP)[41] through establishing ex situ seed collections for Australian tree species. The ASBP is also part of an informal Asia-Pacific network of species conservation through seed-banking.

Other seed banks

Some state government forestry departments routinely store seed of key forestry timber species, including for assisting forest regeneration after bushfire or commercial harvest.

[38] awe.gov.au/sites/default/files/documents/threatened-species-strategy-year-5-report.pdf
[39] rbgsyd.nsw.gov.au/science/australian-plantbank-1/our-collections
[40] kew.org/science/collections/seed-collection/about-millennium-seed-bank
[41] brahmsonline.kew.org/msbp/Projects/Trees; see also brahmsonline.kew.org/msbp/Where/Australia

Map 2 Location of major ex situ conservation facilities for Australian flora



Image, CAM Graphics; reproduced with permission from Martyn Yenson et al. (2021).
Facilities include ASBP Partners, the Australian Tree Seed Centre, the Australian Grains Genebank and Australian Pastures Genebank, and major forestry seed banks with conservation collections.

1. *George Brown Darwin Botanic Gardens conservation seed bank
2. *Alice Springs Desert Park
3. *Western Australian Seed Centre, Department of Biodiversity, Conservation and Attractions, Kensington, and Kings Park and Botanic Garden
4. Forest Products Commission Seed Centre
5. Australian Pastures Genebank, South Australian Research and Development Institute
6. *South Australian Seed Conservation Centre, Botanic Gardens and State Herbarium of South Australia (BGSH)
7. *Australian Grains Genebank, Agriculture Victoria
8. *Victorian Conservation Seedbank, Royal Botanic Gardens Victoria
9. Tasmanian Seed Centre, Sustainable Timber Tasmania
10. *Tasmanian Seed Conservation Centre, Royal Tasmanian Botanical Gardens
11. *National Seed Bank, Australian National Botanic Gardens
12. Australian Tree Seed Centre, CSIRO
13. *Australian PlantBank, Australian Institute of Botanical Science, Royal Botanic Gardens and Domain Trust
14. *Brisbane Botanic Gardens Conservation Seed Bank, Brisbane Botanic Gardens, Mt Cootha.

*, ASBP partner.

SeedEnergy is a privately owned seed business focused on supplying plantation companies with genetically superior seed. The company focuses on major commercial forestry plantation species (*Pinus radiata, E. globulus* and *E. nitens*) but also has seed orchards for other species with commercial potential (*Corymbia maculata, C. variegata*, and *E. cladocalyx*).

Nindethana Australian Seeds, owned by Greening Australia (a national non-government organisation), offered as at 2016 over 3,000 species, and 5–6 regional collections (about 40–50 species each), including forest tree and understorey species, for restoration plantings. Greening Australia also maintains seed collections of species to be used for revegetation purposes[42].

7.3.2 Seed orchards

In commercial forestry, seed orchards are planted and managed to produce quantities of improved seed for tree breeding and plantation stocking. They may be derived from thinned provenance and progeny trials, or planted using select seed or clonal material. Seed orchards are managed for seed supply by a variety of organisations and agencies, including CSIRO, government forestry departments and private companies.

Table 6 shows the number and area of seed orchards for native species grown in forestry plantations in Australia, including some available for seed but not currently actively managed for tree breeding purposes. In addition, Australia has seed orchards of *Eucalyptus viminalis, Khaya senegalensis, Macadamia integrifolia*, *Pinus caribaea, P. elliottii* and *Casuarina obesa*, however national data on area and number is not available for these species.

The number of orchards and provenance trials for Australia's main commercial wood species has declined over the past decade, due to a combination of factors. This includes loss due to fire, cyclones and land-use change, and changing priorities for tree improvement and breeding. Furthermore, provenance and progeny trials and seed orchards have a limited lifespan and can be replanted with more recent genetics, or not replaced depending on priorities at the time.

Some seed orchards (generally of unpedigreed material) have also been established by conservation departments and non-governmental organisations involved in species translocations and revegetation. Orchards of Kakadu plum have recently been established[43].

7.3.3 Seed stands and seed production areas

Australia interprets 'seed stand' as a group of trees (usually wild) chosen for desirable characters and set aside as a seed source. A seed stand therefore differs from a seed orchard planted especially for the production of abundant quantities of superior seeds.

Commercial forestry in Australia does not have identified and registered seed stands. Seed is either collected from native forest under a permit system (but not from specific 'seed stands'), or sourced from plantations and seed orchards.

Seed production areas (SPAs) are areas planted with native plants in order to harvest seed (Baker 2021). SPAs differ from seed orchards in not using genetically improved material. Cultivation and maintenance of SPAs uses a horticultural or agricultural approach to produce seed crops. SPAs make up only a small part of Australia's native seed industry (Baker 2021), but are becoming increasingly important as seed sources for conservation plantings (Hancock et al. 2020). Conservation and revegetation plantings are also becoming important seed production areas (Brad Potts, University of Tasmania, pers. comm. 2021).

In Australia, seed grown from SPAs is primarily used for conservation plantings (vegetation restoration) but also for functional and amenity landscaping, bush food and fodder markets (Hancock et al. 2020). Of the 130 SPAs surveyed by Baker (2021), most grew trees (63%). SPAs contained an average of 10 species.

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[42] greeningaustralia.org.au/what-we-do/our-services/seed-bank-and-native-plant-nursery
[43] naakpa.com.au/

Table 6 Native plantation species in seed orchards in Australia

Species	Seed orchards		
	Number	Generation [a]	Area (hectares)
Araucaria cunninghamii [b]	9	1, 1.5, 2, 3	25
Corymbia citriodora subsp. *citriodora*	1	1	2.3
C. citriodora subsp. *variegata*	10	1 and 1.5	27
C. henryi	3	1	3
C. maculata	9 (including 1 CSO)	1 or 2	15.06
C. torelliana	2	1	3
Eucalyptus argophloia	3 +1 SSO	1 ,2	5.5
E. benthamii	5	1,2	~10
E. botryoides	2	1	0.76
E. camaldulensis	3	1	>1.81
E. cladocalyx	>15	1	19.38
E. cloeziana	2	1	7
E. dunnii	13 (including 1 CSO)	1,1.5	27.04
E. globulus	20	1-4	53.85
E. grandis	5	1, 1.5	9.04
E. kochii	22	1	-
E. loxophleba subsp. *lissophloia*	12	1	22.25
E. marginata	2	1	3.17
E. moluccana	1 CSO	n.a.	-
E. nitens	14	1-3	28.05
E. occidentalis	10	1	5.58
E. pilularis	5	1	15
E. polybractea	>18	1	>17.4
*E. punctata (*previously *E. biturbinata*)	1	1	0.5
E. saligna	7	1	12.85
E. sideroxylon	3	1	2.44
E. smithii	3	1	7
E. tricarpa	5	1	4.13
Grevillea robusta	2	1,1.5	1.25
Santalum album [c]	5	1, 1.5	21.2
S. lanceolatum	2	11	0.4
S. spicatum	5	1	8.77

-, no data; CSO, clonal seed orchard; SSO, seedling seed orchard; n.a., not applicable.
[a] Generation refers to first, second, third, etc. breeding cycle in the seed orchard. An entry of 1.5 indicates the orchard is a mix of first-generation seed (wild seed) and improved seed from a first-generation seed orchard.
[b] *A. cunninghamii* data are from MIG and NFISC (2018).
[c] *S. album* is native to northern Australia, Timor and India. However, the seed orchards in Australia are unlikely to contain any local provenances.
Source: Status as at December 2020, based on consultation with organisations listed in **Table 7**.

In Australia, SPAs are typically operated by private organisations, community groups, government agencies, environmental non-government organisations, and Landcare networks (Hancock et al. 2020). Greening Australia manages small SPAs to produce seed for biodiversity restoration plantings, including for revegetation and for mine site rehabilitation. All of the 29 forestry SPAs established in northern Australia between 1988 and 1991 (Harwood et al. 1993), containing four acacia, two eucalypt and one casuarina species, have since been lost due to cyclone damage, as was the seed orchard of *Acacia auriculiformis* (Harwood et al. 1991), or transferred into national parks.

7.3.4 Provenance trials

For forestry species, genetic diversity is also maintained in numerous field trials spread across temperate and tropical Australia managed by state forestry agencies and by individual companies and partnerships, including Tree Breeding Australia. The trials are mainly provenance and progeny trials for tree improvement and tree breeding of wood-producing and oil-producing plantation species. Species in these trials include *Pinus radiata, P. caribaea, P. elliottii* and hybrids*, Eucalyptus globulus, E. nitens, E. grandis* and *Corymbia citriodora* (see also **Table 7**). Some of the genetics research trials in Tasmania act as both conservation plantings and seed orchards.

Provenance trials have also been established to inform conservation plantings (see **Chapter 9**). Greening Australia is currently working with university researchers and others on provenance selection suited to future climate change scenarios, to inform seed collection for biodiversity plantings (see **Chapter 10**).

7.3.5 Living collections and species conservation plantings

Living collections

Living collections are managed by state, territory and regional botanic gardens and herbaria, to conserve individuals of selected species, as well as for propagation, public education and research purposes. Living collections are particularly important for species[44]:

- that have poor seed quality or do not produce seed
- that have recalcitrant (desiccation-sensitive) seeds that cannot be stored in a seedbank (including many rainforest species)
- that are intended for transplanting (requiring large quantities of plants)
- for which genetic diversity is at risk in the wild
- that have been (or will be) impacted by threats in the natural habitat
- that take a particularly long time to reproduce.

Living collections can be established by sowing seed, taking cuttings or suckers, using tissue culture, grafting rare plants onto more common root stock, or transplanting from other locations. Using seed is preferred as it offers the greatest potential to capture genetic diversity. A small number of the species on the FAO list of forest genetic resources for Australia are held as living collections by Australia’s national and state herbaria, including *Davidsonia pruriens*, *Macadamia* spp, and *Syzygium paniculatum*.

Conservation plantings

Conservation plantings have been established for Australia’s key plantation species to help protect genetic material, generally using unpedigreed seed or clonal plantings. Grafted trees of *E. globulus* have been planted in the National Genetic Resource Centre for plantation forestry at Mount Gambier, South Australia. Other examples are provided in **Chapter 9**. Several threatened tree species have also been planted in conservation stands as part of forestry tree breeding infrastructure.

Conservation stands (or 'field genebanks') have also been established by some government environment departments[45] and non-government organisations to assist in the conservation of

[44] rbgsyd.nsw.gov.au/science/rainforest-conservation-research/rainforest-seed-conservation-project/sensitive-seeds!/living-collections

threatened plant species. The aim is that these stands provide material for translocation and restoration and act as a safeguard against extinction in the wild. As with living collections, species that are highly threatened in the wild, and species that do not readily produce seeds, are a high priority for planting in conservation stands.

In some cases conservation plantings, even if not established specifically as formal seed orchards, are proving an important source of seed. For example, one planting of *E. morrisbyi* on private land is proving invaluable as a source of seed to restore the main population of the species, which has declined recently (B. Potts, University of Tasmania, pers. comm. 2021).

Translocations

Translocation is the deliberate transfer of plant material (seeds, cuttings or propagated seedlings) from one area to another for the purpose of conservation, to help protect genetic material and reduce the risk of species extinction. Translocations can involve restocking declining populations at a site where the species already occurs (augmentation), restoring an extinct population at a site where the species used to occur (reintroduction), or establishing new populations in areas of similar or appropriate habitat that have greater long-term security (introduction)[46]. Introductions can occur at sites within or outside the known distribution range for the plant species.

Government environment departments and agencies have established translocation plantings of selected threatened species, including *Acacia cochlocarpa* and *Wollemia nobilis*[47]. ASBP partners were involved in numerous translocation and restoration trials across Australia, although many were lost due to bushfire in 2019-20; work is underway to re-establish some of these plantings. The *Guidelines for the Translocation of Threatened Plants in Australia* (Commander et al. 2018) provide guidance on best-practice translocations for Australian native species.

7.3.6 Biodiverse restoration plantings

Biodiverse restoration plantings, using good quality seed from known and appropriate locations and parentage, are increasingly contributing to the conservation of forest genetic resources.

Several Australian guidelines encourage best practice in seed collection, handling and storage[48], tissue culture, cryopreservation, and restoration plantings, including choice of material to anticipate climate change (Hancock et al. 2016; SERA 2017; Martyn Yenson et al. 2021).

Land clearing and forest fragmentation in Australia have reduced the connectivity between populations and contributed to the loss of gene pools and genetic variability in tree species (see **Chapter 5**). Biodiverse restoration plantings increase the area of native vegetation, increase connectivity between habitat, and improve gene flow and ecosystem health. Private and government organisations are involved in biodiversity restoration work, including creating corridors to maximise vegetation connectivity, facilitate ongoing movement of biota and increase their capacity to adapt to climate change.

Greening Australia and other non-governmental organisations are working with farmers, landholders, regional natural resource management organisations and governments on restoration planting and native vegetation management for biodiversity conservation.

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45 dpaw.wa.gov.au/about-us/science-and-research/plant-conservation-research/258-flora-translocations
46 dpaw.wa.gov.au/about-us/science-and-research/plant-conservation-research/258-flora-translocations
47 anpc.asn.au/translocation-case-studies/
48 see greeningaustralia.org.au/florabank for example

For example, the Gondwana Link project[49] involves conservationists, property owners and community groups working together to create a 1000-kilometre continuous corridor of bushland in southern Western Australia, and the Great Eastern Ranges (GER) corridor initiative[50] is working to protect, connect and restore landscapes across 3,600 kilometres of eastern Australia.

7.4 Challenging species

7.4.1 Rainforest species, native foods and botanicals

Several native Australian species used for food, farm forestry, timber and other purposes are rainforest species. Examples are *Backhousia citriodora*, *Castanospermum australe*, *Davidsonia pruriens*, *Duboisia myoporoides*, *Eucryphia lucida, Flindersia australis, Fontainea picrosperma*, *Macadamia* spp*.*, *Podocarpus elatus*, *Syzygium leuhmanii*, *S. anisatum* and *Tasmannia lanceolata*.

A significant proportion of rainforest species have recalcitrant seeds that are not tolerant of desiccation and cold storage, or that are comparatively short-lived in storage (e.g. Sommerville et al. 2017). Seed of these species is collected as needed and when seasonal production and access permit, and generally used for prompt propagation (e.g. Lott et al. 2005). In some cases, difficult species can be stored via tissue culture or cryopreservation[51].

7.4.2 Macadamia

Macadamia integrifolia, which is both a commercial species and a threatened species, is conserved ex situ as part of both tree breeding and species recovery programs (see below and **Chapter 9**).

Macadamia species can be grown from seed, but plantations of macadamia trees for commercial production of the edible kernel (the macadamia 'nut') are propagated clonally. The clonal trees usually consist of a scion (young shoot) grafted onto a seedling rootstock of cultivars 'H2' or 'Beaumont'. Commercial nurseries supply grafted stock for domestic use and commercial plantations. Clonal trees for conservation and research purposes can also be produced using rooted cuttings.

Ex situ conservation plantings and breeding trials of *Macadamia* were planted between 1997 and 2019 in various locations in northern New South Wales and south-eastern Queensland (Topp 2019). The National Macadamia Germplasm Collection is located in Tairo, Queensland, and Alstonville, New South Wales.

7.4.3 Threatened species

As outlined above and in **Chapter 6** and **Chapter 10**, government environment departments and conservation organisations manage conservation of threatened species, including ex situ conservation. A range of other organisations, including the Australian Tree Seed Centre (ATSC), Forestry Corporation of New South Wales, Sustainable Timber Tasmania and the Queensland Government Department of Agriculture and Fisheries, also maintain ex situ seed orchards and conservation plantings for several rare and endangered tree species. Species in these conservation plantings and seed orchards include Queensland western gum (*E. argophloia*), Barber's gum (*E. barberi*), Camden white gum (*E. benthamii*), Brooker's gum (*E. brookeriana*), Morrisby's gum (*E. morrisbyi*), spinning gum (*E. perriniana*), Risdon peppermint (*E. risdonii*),

[49] gondwanalink.org/
[50] ger.org.au/
[51] rbgsyd.nsw.gov.au/Science/Australian-PlantBank-1

varnished gum (*E. vernicosa*), Wally's wattle (*A. pataczekii*) and lemon myrtle (*Backhousia citriodora*). A conservation planting of Miena cider gum (*E. gunnii* subsp. *divaricata*) in Tasmania was destroyed by possums during the period 2011-2016.

The ATSC manages an ex situ gene-bank of *E. benthamii*, which is important for conservation but also for potential commercial development of the species. SeedEnergy is commencing a collaboration with ATSC to provide an additional site for ex situ conservation of *E. benthamii.* Two trials of *E. risdonii* can act respectively as a conservation planting (established by the University of Tasmania) and a seed orchard (established by Sustainable Timber Tasmania). The main wild population of the rare Tasmanian endemic *E. morrisbyi* has declined, and the University of Tasmania has established conservation plantings of this species.

7.5 Macadamia case study[52]

All four species in the genus *Macadamia*, family Proteaceae, are native to Australia, and are endemic to the coastal ranges and foothill forests of north-east New South Wales and south-east Queensland, in subtropical rainforest and in sclerophyll forest containing subdominant subtropical rainforest. The four species are closely related. Genetic differentiation between populations has occurred as a result of past climate change, site adaptation and limited gene flow (Hardner et al. 2009).

The four macadamia species are listed under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*, with three species (*Macadamia integrifolia*, *M. ternifolia* and *M. tetraphylla*) listed as Vulnerable and the rarest macadamia, *M. jansenii,* listed as Endangered. A recovery plan has been operating since 2009 (Costello et al. 2009) and an updated recovery plan is in preparation (Powell and Gould 2019). *Macadamia jansenii* is a target species under Australia's Threatened Species Strategy[53]. Three of the *Macadamia* species are also listed on the IUCN Red List of threatened species[54]: *M. ternifolia* and *M. tetraphylla* as Endangered, with a decreasing population trend for *M ternifolia*, and *M. integrifolia* as Vulnerable.

The natural distributions of *M. integrifolia*, *M. ternifolia* and *M. tetraphylla* overlap. *Macadamia jansenii* is only known to occur in Bulburin National Park, Queensland, 150 kilometres north of the nearest populations of the other species, and has a population of fewer than 200 individuals in a highly restricted habitat; it is most closely related to *M. ternifolia*.

It is estimated that over 80% of the wild macadamia population in Queensland, and 98% of the wild macadamia population in New South Wales, has been lost since European settlement[55]. Clearing of rainforests has also led to fragmentation and isolation of rainforest remnants, causing a decrease in genetic diversity within remnants and decreased gene flow between them.

Threats to macadamia in the wild include further habitat loss and fragmentation through vegetation clearing, inappropriate fire regimes, and weed invasion. Potential genetic threats are inbreeding within populations, loss of fertility due to isolation and habitat fragmentation (Powell et al. 2014), and introgression through hybridisation of horticulture cultivars with wild populations (O'Connor et al. 2015).

52 Updated from the case study in *Australia's State of the Forests Report 2018*, pp.151-152, awe.gov.au/abares/forestsaustralia/sofr/sofr-2018
53 awe.gov.au/environment/biodiversity/threatened/publications/100-priority-species
54 iucnredlist.org
55 wildmacadamias.org.au

Macadamia nuts are traditionally a valuable food and cultural resource for Indigenous peoples, who shared and traded the nuts with early European settlers. Settlers began planting *M. integrifolia* and *M. tetraphylla* from seeds of local wild stock in the 1860s. Through tree breeding and genetic improvement, and the development of mechanical de-huskers and nut-crackers, macadamia nuts have become a highly valued international commercial food crop. Macadamia are contributing to livelihoods and food security both domestically and internationally.

Australia and South Africa are the world's leading producers of macadamia nuts, with Australia's industry worth $280 million per year. The area of macadamia orchards in Australia increased from 17 thousand hectares in 2010 to 33 thousand hectares in 2020[56].

Most of the world's commercial macadamia orchards originated from a small number of individual trees[57]. Due to the widespread use of grafting, much of the plantation estate is genetically uniform. In 2019, a few trees near Gympie, Queensland, were identified as the likely origin of 70% of the world's macadamias (Nock et al. 2019). Commercial macadamia root stock potentially has an even narrower genetic base.

Domestic and international breeding of commercial macadamia nut will be facilitated through broadening the genetic base through access to wild *Macadamia* populations (Mai et al. 2020). In situ conservation of populations of the four *Macadamia* species is thus important commercially, as well as for their conservation. All recorded sites for *M. jansenii* are protected, but only a proportion of the recorded sites for *M. integrifolia*, *M. ternifolia* and *M. tetraphylla* are protected. Of particular concern for conservation of the original genetic composition of *M. tetraphylla* is that less than 4% of the known sites for this species are isolated from the potential to cross-breed with commercial cultivars.

An ex situ collection of *Macadamia* was planted in 2001 under the National Macadamia Germplasm Conservation Program to conserve a sample of the remaining genetic variation, and provide source material for introduction of new genetic material into future breeding programs (Hardner et al. 2009). The collection was heavily weighted towards *M. integrifolia, M. tetraphylla* and their hybrids. Of these plantings, 302 accessions from 75 locations survive in two government research plots (Mai et al. 2020). The Macadamia Conservation Trust is currently working to secure genetic material from a wider range of sites and to increase the representation of *M. ternifolia* in a new Wild Macadamia Arboretum.

Due to the extreme rarity of *M. jansenii*, the Macadamia Conservation Trust has partnered with the Australian Government, botanic gardens, the University of the Sunshine Coast and philanthropic organisations to grow ex situ populations as insurance against loss of wild populations, such as in bushfires. Cuttings from 42 plants of *M. jansenii* (taken under licence from the Queensland Government) are growing at Gladstone's Tondoon Botanic Gardens. *M. jansenii* has also become a model for studying the genetics of rare species, providing information about impacts of small population size and associated genetic bottlenecks[58].

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[56] australianmacadamias.org/industry/about/about-the-macadamia-industry; australianmacadamias.org/industry/facts-figures/australian-macadamias-year-book-2020
[57] abc.net.au/news/rural/2019-05-30/macadamia-research-nuts/11160786
[58] qaafi.uq.edu.au/article/2021/02/critically-endangered-macadamia-species-becomes-plant-supermodel

7.6 Needs, challenges and opportunities

Challenges to ex situ conservation in Australia include variable seed production, species with recalcitrant seeds (seeds with poor storage capacity, especially tropical species), land-use change, climate change, drought, bushfire, long distances between native species habitat and infrastructure, and decreased investment in tree breeding.

Given the current and likely increase in risk due to climate change, drought and fires, the main needs for ex situ conservation of forest genetic resources are to maintain the existing efforts for current and promising species, and to increase off-site conservation efforts for other key species.

Increased efforts will require sufficient seed for tree breeding and conservation plantings, noting that constraints for native seed supply include (Hancock et al. 2020):

- future demand for seed difficult to meet from wild harvest
- markets unwilling to pay for the true cost of seed collection and production
- lack of available seed
- inconsistent and/or unpredictable demand for seed.

In the native seed sector, more seed of native species is collected from private property than from other land tenures. Collection levels are lowest in national parks (Hancock et al. 2020). Some collections are made sufficiently broadly to not be considered 'local provenance'. Lastly, wild-collected seed is not commonly tested to determine its quality (Hancock et al. 2020).

To meet any shortfalls in demand for conservation plantings, seed should come from specifically managed seed-production areas (SPAs) rather than wild populations (Hancock et al. 2020). This requires ongoing funding and consistent management of SPAs, expert design of SPAs, and accessible seed cleaning facilities.

Opportunities also exist for increased ex situ conservation through the use of PlantBank and other seed bank facilities, and through encouraging community participation in organised seed collection and ex situ site establishment.

7.7 Priorities for capacity-building

Priorities for capacity-building and research include:

- funding of and training in genetic conservation
- building capacity to establish and maintain seed production areas
- ex situ conservation of a wider range of species, including through seed collection and storage
- improved documentation of the provenance of seed collected for conservation plantings
- regular seed viability testing (where quantities allow)
- provenance trials to investigate the climate-change tolerance of key species
- establishment of ex situ conservation areas in locations predicted to be suitable in future climates.

8 State of use of forest genetic resources

8.1 Key points

- Harvest permits, codes of practice and management plans are used by Australian, state and territory governments and private companies to manage sustainable use and harvest within Australia's native forests and plantations. Plantations contributed 87% of Australia's total sawlog and pulplog harvest in 2019-20.
    - For the period 2011-12 to 2015-16, the volume of sawlogs harvested from public native forests was within sustainable yields for New South Wales, Tasmania, Victoria and Western Australia and within the allowable cut in Queensland.
    - There is insufficient information to assess sustainable wood harvest yields from private native forests, but the national harvest from private native forests has declined progressively since the period 2001-06.
    - There are no comprehensive national data on the use of non-wood products from native forests, because most of these industries are small-scale and dispersed.
- Legislation and policies are used to manage access to, and the exchange of, plant reproductive material and intellectual property.
    - In 2002, all Australian governments endorsed the Nationally Consistent Approach for Access to and the Utilisation of Australia's Native Genetic and Biochemical Resources, to promote consistency in regulating and managing access to genetic resources.
- Within Australia, forest reproductive material is obtained mainly from seed collected in native forests, and from commercial plantations and seed orchards for plantation species. Seed is also supplied from some conservation plantings that have been converted to seed production areas.
    - The production of seed for plantation tree breeding meets demand, but there is a shortage of seed for restoration plantings. Australia's climate variability, seasonal factors and funding constraints contribute to this seed shortage.
    - Australia exports seed, mainly of acacia and eucalypt species, to a range of countries for research and for plantation establishment.
    - Australia imports a small quantity of forest reproductive material for research trials and plantations.
    - Australia mostly relies on industry self-regulation for ensuring high-quality seed is sold to growers.
- Needs, challenges and opportunities for the use of forest genetic resources relate to sufficient seed supply, and understanding climate-adapted provenances.
- Priorities for capacity-building and research include improved methods for testing germplasm for freedom from pathogens, improved data on sustainable yields from private native forests, including Indigenous lands, and supporting the development of Indigenous businesses based on wild harvest of traditional foods and medicinal plants from forests.

8.2 State of use of forest genetic resources

Harvest permits, codes of practice and management plans are used by Australian, state and territory governments and private companies to manage sustainable use and harvest within Australia's native forests and plantations.

The annual plantation log harvest and the total contribution of plantations to Australia's total sawlog and pulplog harvest have both increased steadily since 2000-01. Plantations contributed 87% of Australia's total sawlog and pulplog harvest in 2019-20 (ABARES 2020b).

For the period 2011-12 to 2015-16, the volume of sawlogs harvested from public native forests was within sustainable yields for New South Wales, Tasmania, Victoria and Western Australia and within the allowable cut in Queensland (MIG and NFISC 2018). No harvesting of public native forests occurs within the Australian Capital Territory, the Northern Territory or South Australia.

Sustainable yields and actual harvests of sawlogs from public native forests are both declining over time due to a range of factors, primarily the transfer of forests into nature conservation reserves, but also increased restrictions on harvesting, revised estimates of growth and yield, and impacts of occasional, intense broad-scale bushfires (MIG and NFISC 2018).

The national harvest from private native forests has declined progressively since the period 2001-06. However, there is insufficient information to sustainable wood harvest yields from private native forests.

There are no comprehensive national data on the use of non-wood products from native forests, because most of these industries are small-scale and dispersed (MIG and NFISC 2018). Harvest of non-wood forest products is managed under state and territory regulations and permit systems. High-value products include wildflowers, seed, honey and aromatic products obtained from tea tree and sandalwood, and harvest data are available for some of these.

Kakadu plum (*Terminalia ferdinandiana*) is an emerging commercial product that is being harvested from the wild, largely by Indigenous communities. Assessment of demand, relative to the abundance of the trees and quantity of fruit products, suggests that currently the risk of widespread, uniform over-harvest is low (Gorman et al. 2016), but there is a risk of localised overharvest at accessible high-density sites (Whitehead et al. 2006).

8.3 Access to Australian forest genetic resources: legislation and policies

8.3.1 Access to in situ native plant material

In Australia, the Australian, state and territory governments have responsibility for access to in situ native genetic resources within their jurisdiction.

The Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) regulates access to the genetic resources of native species in Commonwealth areas[59] in a manner consistent with the Convention on Biological Diversity. Each state or territory government

[59] awe.gov.au/science-research/australias-biological-resources/access-biological-resources-commonwealth

manages access to biological resources in its jurisdiction under its own laws, including regulating collection of forest materials (bark, leaves, flowers, seed etc) through permit systems.

Permit conditions vary depending on land tenure and the threatened species legislation of the relevant jurisdiction, and will often include conditions that only allow material to be used for conservation, restoration and/or scientific research activities. Examples of legislative frameworks that regulate access to genetic resources and benefit sharing are the *Biodiscovery Act 2004 (Qld)* and the *Biological Resources Act 2006 (NT).*

In 2002, all Australian governments endorsed the Nationally Consistent Approach for Access to and the Utilisation of Australia's Native Genetic and Biochemical Resources[60], to promote consistency in regulating and managing access to genetic resources. One of the aims of the approach is to ensure that the benefits of access are equitably shared between providers and recipients.

In 2005, the Australian Government introduced regulations under the EPBC Act to facilitate access to, and regulate the use of, its native genetic and biochemical resources[61]. Access for non-commercial or commercial uses of native genetic resources in Commonwealth areas requires a permit[62]. An access permit for commercial use of genetic resources also requires a benefit-sharing agreement between the applicant and the resources provider. This agreement must acknowledge any use of traditional knowledge, and document, as appropriate, the benefit-sharing arrangements associated with use of that traditional knowledge.

8.3.2 Access to ex situ native plant material

The Australian Tree Seed Centre (ATSC[63]) is a major seed bank based at CSIRO, and a key supplier of seed for forestry species (see **Chapter 7**). Supply of seed from the ATSC is subject to relevant state, territory and Commonwealth legislation. Since the early 1960s, the ATSC has supplied more than 200,000 certified seed lots from more than 1,000 tree or shrub species to researchers in more than 100 countries (MIG and NFISC 2018). Until the early 2000s, the ATSC supplied seed free-of-charge to some developing countries, however seed supply is now on a cost-recovery basis.

The Australian Seed Bank Partnership[64] is a national collaboration of 15 organisations, including Australian, state and local government botanic gardens **(Table 5)**. Seeds stored in ASBP conservation seed banks are held in trust as public good collections, to safeguard the genetic diversity of Australia's native species for future generations and for use in research and restoration work.

Seeds for the ASBP are collected under permit, conditions of which will vary depending on the land tenure and the threatened species legislation of the relevant state, territory or Commonwealth jurisdiction where collections are made. Collections may be made on private lands with specific conditions placed on the permitted use of the seeds. It is best practice for collections only to be made once conditions related to access and benefit-sharing arrangements have been agreed with traditional Indigenous owners.

[60] awe.gov.au/environment/biodiversity/publications/understanding-nca-access-and-utilisation-australias-native-genetic-biochemical-resources
[61] awe.gov.au/science-research/australias-biological-resources/access-biological-resources-commonwealth
[62] awe.gov.au/environment/biodiversity/publications/genetic-resources-management-commonwealth-areas
[63] csiro.au/en/about/facilities-collections/collections/atsc
[64] seedpartnership.org.au/

The release of seeds from seed banks requires a formal request and approval process to ensure the seeds released will be utilised for a purpose that fits the intended scope of the original collection permits. If the collections in question are covered by access and benefit-sharing arrangements, further negotiation with Indigenous traditional owners may also be required prior to release.

Access to some seed internationally may be subject to obligations under the Convention for Biological Diversity, and other access and benefit-sharing regimes.

8.3.3 Intellectual property, patents, and Indigenous knowledge

Plant breeder's rights and patents are administered by the Australian Government agency IP Australia[65] under the *Plant Breeder's Rights Act 1994* (PBR Act) and the *Patents Act 1990* respectively. The PBR Act provides intellectual property (IP) protection for new varieties of plants, including trees, that meet the legislative criteria. The period of IP protection for trees and vines is up to 25 years, and for other plant varieties is up to 20 years. The Plant Breeder's Rights (PBR) searchable database[66] contains information on all PBR for varieties in Australia.

A patent is granted for an invention that is new, useful, and involves an inventive step. Scientific research on genetic resources and associated traditional knowledge can lead to patents for new inventions. A disclosure of source requirement for patents is also being explored internationally, through the World Intellectual Property Organisation (WIPO) Intergovernmental Committee on Intellectual Property and Genetic Resources, Traditional Knowledge and Folklore (IGC).

The Australian Government is currently engaging with stakeholders on a range of initiatives relating to management and protection of Indigenous knowledge. This includes investigating options to enhance Australia's intellectual property system to support Indigenous communities to benefit from and protect their Indigenous knowledge, and considering possible legislation to protect Indigenous Knowledge.

8.4 Seed supply and demand

As outlined in **Chapter 7**, Australia's seed banks hold seed for nearly all of the species listed for Australia as forest genetic resources by the FAO, with duplicate collections held for most species. Some species are collected because they are important for usage in plantations overseas, rather than within Australia. Seed held in seed banks may be used for research, commercial or conservation plantings as appropriate according to the purpose for which it was collected.

Within Australia, seed for commercial forestry is obtained mainly collected in native forests under a government permit system, and from plantations and seed orchards for plantation species. Seed is also supplied from commercial seed orchards and some conservation plantings that have been converted to seed production areas.

The production of seed for plantation tree breeding generally meets demand, but there can be a shortage of seed for restoration plantings (see Hancock et al. 2020). Australia's climate variability, seasonal factors and funding constraints contribute to this seed shortage.

Australia exports seed to a range of countries for research and plantations purposes (mainly acacia and eucalypt species). A small quantity of forest reproductive material is imported for research trials and forestry plantations. Import and quarantine regulations differ between

65 ipaustralia.gov.au/
66 ipaustralia.gov.au/plant-breeders-rights/applying-pbr/search-pbr

countries, which can lead to inefficient international transfers of forest genetic resources (Koskela et al. 2014). Quarantine regulations restrict movement of material at risk of containing serious pathogens such as *Austropuccinia psidii* (which causes myrtle rust), and *Fusarium circinatum* (which causes pine pitch canker).

The Nagoya Protocol on Access and Benefit Sharing[67] (see **Chapter 12**) is intended to improve transparency and access to genetic resources. However, it may increase transaction costs associated with lawfully obtaining forest genetic resources for research and development, due to the time needed to obtain the necessary documentation for exchange where countries lack a well-functioning Access and Benefit-Sharing regulatory system (Koskela et al. 2014).

Australia mostly relies on an industry self-regulation model for ensuring high-quality seed is sold to growers. Major suppliers apply seed and propagule collection and hygiene standards consistent with internationally or scientifically recognised standards.

8.5 Needs, challenges and opportunities

Within Australia, key needs are for increased reliability of seed sources for restoration plantings, funding for species genetic characterisation and genetic conservation work, and increased understanding of suitable climate-adapted provenances.

For international exchange, more efficient international transfers of forest genetic resources could occur by harmonising import and quarantine regulations (Koskela et al. 2014). Research and development of more economically viable treatments and testing of germplasm that would allow it to be declared free of serious pathogens would also benefit the movement of germplasm.

The potential exists for Indigenous communities to develop on-country businesses for wild harvest of traditional foods and medicinal plants, such as native plum, eucalypts and *Santalum* species. Challenges include capacity-building, establishing appropriate benefit-sharing agreements with industry partners, access to information or advice about how intellectual property rights could support these businesses, and the establishment of guidelines for the ethical development of wild-harvest businesses.

The use of participatory video has been demonstrated to be a valuable tool in empowering Indigenous communities to document their traditional knowledge, providing authorship to community elders through the production of short documentary films (Thompson 2019). The documentation of a long history of community use may also support regulatory approval of the commercial use of medicinal plants as complementary medicine.

8.6 Priorities for capacity-building and research

Key priorities for capacity-building and research include:

- improved data on sustainable harvest levels from private native forests, including Indigenous-managed lands
- development of commercial enterprises that employ Indigenous communities and appropriately draw on traditional Indigenous knowledge relating to flora.

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[67] The Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity; awe.gov.au/science-research/australias-biological-resources/nagoya-protocol-convention-biological

9 State of genetic improvement and breeding programs

9.1 Key points

- In Australia, the main forest trees for which there are genetic improvement and breeding programs are eucalypts, pines, macadamia and tea tree (*Melaleuca alternifolia)*.
  - The forestry sector maintains active tree breeding and improvement programs for more than 30 native species and varieties, as well as for exotic pines.
  - The most advanced breeding programs (in terms of numbers of breeding cycles and overall sophistication) are for southern blue gum (*Eucalyptus globulus*), shining gum (*E. nitens*), radiata pine (*Pinus radiata*) and Caribbean pine (*P. caribaea* var. *hondurensis*). Depending on the species, selection has been for growth, form, pulp fibre yield, sawn wood traits, frost tolerance, and pest and disease resistance, and has led to progressive increases in yield and value over time.
  - Smaller programs of species evaluation and improvement exist for a range of other species with potential use for pulp, sawlog, biomass or essential oil. Breeding programs have made gains in yield and quality of macadamia nuts and tea tree oil.
  - Provenance trials are used for some forest species of conservation interest, to evaluate growth and survival on different sites and adaptability to climate change.
  - Forest genetic resources have been used to help improve the productivity of Australian and overseas plantations of eucalypts and acacias.
- There has been a shift in the main players involved in forest tree breeding in Australia.
  - Historically, government agencies led species evaluation and tree breeding programs, but their involvement has reduced.
  - A range of private companies and consortia now also operate tree breeding programs for key timber tree species (mainly eucalypt and pine species). Individual companies also run breeding programs for sandalwood (*Santalum*) and for eucalypts used for essential oil production.
  - Universities and the private sector manage tree breeding for macadamia and tea tree in Australia in association with industry representative bodies.
- Increasingly, DNA-based molecular genetic and genomic techniques are being used to assist tree breeding in the forestry, macadamia and tea tree sectors.
  - Most tree breeding programs have historically used recurrent breeding and selection based on quantitative genetic methods.
  - More recently, DNA marker-based techniques are being used for pedigree reconstruction and management, and to accelerate genetic gains by reducing breeding cycles and the number of progeny trials needed.
  - New technologies also support tree breeding, such as near-infrared reflectance spectroscopy for analysis of wood quality.
  - Sophisticated computing is used to process the 'big data' associated with integrated phenotypic and molecular data, and to carry out quantitative genetic analysis of traits and selections (e.g. TREEPLAN software, used by Tree Breeding Australia).
- The needs and challenges for forest tree improvement and breeding in Australia are:
  - ensuring ongoing access to in situ genetic material, and protecting in situ and ex situ material from risks such as introduced diseases, land-use change and bushfire

- ongoing breeding and improvement of commercial plantation species to help industries adapt to changes in markets, products and climate
- monitoring the susceptibility of eucalypts, tea tree and lemon myrtle to myrtle rust
- evaluating key plantation and threatened species for climate change adaptability
- developing reliable, cheap phenotyping methods for biomass and oil content determination in tea tree and sandalwood
- integrating tree breeding with product evaluation and development.

- Opportunities for tree improvement include ongoing collaboration on tree breeding, more rapid breeding with the assistance of marker-based techniques, improvement of new species, and improving plantation material using wild genetic material.
- Priorities for capacity-building include training and employment opportunities in tree breeding, including for younger workers.

9.2 Genetic improvement and breeding

Genetic diversity within a species enables breeding populations to adapt to changing environments and selection pressures (Stoutjesdick 2013).

Breeding programs benefit from a base population with broad genetic diversity. Tree breeders thus seek access to genetic resources from the wild (natural habitats) or from ex situ resources established to store wild or selected genetic material, such as seed banks, tissue cultures, or conservation plantings.

For initial breeding work, broad sampling of the species enables evaluation and assessment of the extent of genetic variation, and provides progeny (offspring) populations of sufficient merit to enable initial tree improvement (Nikles et al. 1994). As well as variation among individuals, a tree species may have separate populations at different localities, termed provenances, which differ in their genetic diversity. Sampling should consider the population sizes, geographical and ecological range and discontinuities, genetic diversity, and breeding system of the species (Nikles et al. 1994, Hamrick 1994).

A number of Australia's native forest species are grown in plantations, and for these species a substantial proportion of the wild genetic base has been tested and integrated into seed collections, seed orchards and breeding programs. For exotic pine species grown in plantations in Australia, tree breeding benefited from earlier seed collections from source countries, but further import is now difficult due to quarantine restrictions. For a few species, genetic diversity is conserved ex situ as tissue cultures (for example, hoop pine *Araucaria cunninghamii*, and the endangered horticultural species Wollemi pine, *Wollemia nobilis*) or clones (e.g. *Pinus caribaea, P. elliottii, A. cunninghamii*).

Often, provenance and progeny trials are used to evaluate the suitability of a species for a site or range of sites, and to identify the genetic diversity and variation in traits within a species. Over the past century, Australia has evaluated a wide range of species for their prospects for forestry, agroforestry (farm forestry), biomass production, conservation planting, and saline-site rehabilitation (e.g. Warren 1964; Cremer 1969; Booth and Saunders 1984; Carron 1985; Burgess 1988; Nikles 1996, Harwood et al. 2001, 2007; Boardman et al. 2002; Bush et al. 2009; Dieters et al. 2007; Wu et al. 2007; Carr 2009; Clark et al. 2009; Clarke et al. 2009; Hobbs and Bennell 2009; O'Brien et al. 2007; Lee et al. 2010; Bush 2011; Hendrati et al. 2011). As a result, Australia has good knowledge of the early growth and site performance of a wide range of native and exotic forest tree species and, for some of these species, good knowledge of their longer-term growth and performance. However, there is a bias towards information on better quality sites in southern Australia suitable for growing trees for sawn timber and pulplogs. Information on drier and more tropical sites, and species that might be suitable for non-traditional products and services (e.g., essential oils, biochemicals, biomass, carbon sequestration), is less comprehensive.

Once the species or individuals with the best traits have been identified, a breeding program may commence to select and genetically improve the material, for example through cross-pollination to introduce desirable characteristics, analysis to understand heritability, and production of elite breeding lines or hybrids.

Typically, a number of objectives are pursued simultaneously for a breeding program for any crop (Stoutjesdick 2013), including:

- increasing yields
- improving fibre or timber quality
- adapting to environmental stresses
- protecting plants against changing or evolving pests and diseases.

Because trees have long maturation and generation times and, sometimes, poor juvenile-mature trait correlation (Thumma et al. 2010), the characteristics being selected often take years to reveal their qualities. This means traditional tree breeding is a long-term process. For example, it can take 3-6 years before harvest of oil from mallee eucalypt plantations (e.g. Herbert 2000); 15 years until peak nut production for macadamia plantations (Topp 2019); 12-15 years until harvest of short-rotation plantations for wood pulp; and 20-40 years for harvest of sawn logs from pine plantations. However, technology and modern genetic techniques are increasingly being used to inform, accelerate and assist tree breeding.

9.3 Tree breeding and improvement for pulp and sawn wood species in Australia

Currently, there are active tree breeding and improvement programs for more than 30 native Australian wood-producing species and varieties. The main Australian species involved are *Corymbia citriodora* ssp. *variegata*, *C. henryi*, *C. maculata*, *Eucalyptus cladocalyx*, *E. cloeziana*, *E. dunnii*, *E. globulus*, *E. grandis*, *E. nitens*, *E. occidentalis*, *E. saligna* and *E. sideroxylon/E. tricarpa*. There are also active programs for the exotic *Pinus caribaea* and hybrids, and *P. radiata.* **Table 7** and **Table 8** list the main native and exotic species, respectively, currently in tree improvement programs in Australia, and the organisations involved. There is also a small tree improvement program for *Santalum album*. *Khaya senegalensis* (in Northern Territory; Nikles et al. 2014) and *Pinus brutia* and *P. pinaster* (Butcher 2007) are exotic species previously included in small breeding programs.

The most developed breeding programs (with 2-4 generations, now often managed on a 'rolling front') are for Australia's major plantation species, that is, *Araucaria cunninghamii*, *E. globulus*, *E. nitens*, *P. radiata,* and *P. caribaea* and hybrids. Second-generation trials exist for *Corymbia maculata* and *Eucalyptus benthamii*, but most of the other species in **Table 7** are at first-generation selection stage. Significant other tree-breeding work occurs in other countries that have plantations of Australian species.

Table 7 Native plantation species in tree improvement or breeding programs in Australia

Species[a]	Agency
Acacia melanoxylon	PIRSA
Araucaria cunninghamii	Queensland DAF[b]
Corymbia citriodora subsp. *citriodora*	Queensland DAF
C. citriodora subsp. *variegata*	Australian Low Rainfall Tree Improvement Group[c], CSIRO, Queensland DAF, Seed Energy
C. henryi	CSIRO, Queensland DAF
C. maculata	CSIRO, Australian Low Rainfall Tree Improvement Group, PIRSA, Seed Energy
C. torelliana	Queensland DAF
Eucalyptus argophloia	Queensland DAF, CSIRO
E. astringens	PIRSA
E. benthamii	CSIRO, SeedEnergy
E. botryoides	PIRSA
E. camaldulensis	Australian Low Rainfall Tree Improvement Group, CSIRO, PIRSA, Queensland DAF
E. cladocalyx	Australian Low Rainfall Tree Improvement Group, CSIRO, PIRSA, Seed Energy
E. cloeziana	Queensland DAF
E. dunnii	CSIRO/Forestry Corporation of New South Wales (jointly), SeedEnergy, Queensland DAF
E. globulus	Australian Bluegum Plantations, HVP Plantations, Tree Breeding Australia[d] (in partnership with Forico, PF Olsen, Sustainable Timber Tasmania, and WA Plantation Resources (WAPRES))
E. grandis	CSIRO, Queensland DAF
E. leucoxylon	PIRSA
E. longirostrata	Queensland DAF
E. nitens	Forico, SeedEnergy, Sustainable Timber Tasmania, HVP Plantations
E. occidentalis	CSIRO, Australian Low Rainfall Tree Improvement Group, PIRSA
E. pilularis	Queensland DAF
E. polybractea	CSIRO, private industry
E. punctata (previously *E. biturbinata*)	Queensland DAF
E. saligna	CSIRO
E. sideroxylon	Australian Low Rainfall Tree Improvement Group, CSIRO, Queensland DAF
E. smithii	Australian Bluegum Plantations, CSIRO, SeedEnergy, WA Plantation Resources
E. tereticornis	Queensland DAF
Grevillea robusta	CSIRO/Queensland DAF (jointly)
Melaleuca uncinata	PIRSA
Santalum lanceolatum	University of the Sunshine Coast
S. spicatum	Forest Products Commission (WA)

CSIRO, Commonwealth Scientific and Industrial Research Organisation; DAF, Queensland Department of Agriculture and Fisheries; PIRSA, Primary Industries and Regions South Australia
[a] Data as at December 2020. All of these species are on the FAO list of forest genetic resource species for Australia.
[b] The *Araucaria cunninghamii* breeding program is on hold due to organisational changes and other higher priorities.
[c] The Australian Low Rainfall Tree Improvement Group was formed in 1999 as a partnership between CSIRO and several industry and state forestry organisations in southern Australia. Although external funding ceased in 2009, a range of trials established under this group remain managed by the host organisations.
[d] Tree Breeding Australia partners in *E. globulus* breeding are Forico, PF Olsen, Sustainable Timber Tasmania, and WA Plantation Resources.
Source: Information was sourced from replies to data requests sent to plantation owners and managers listed in this table as well as HQPlantations; Midway; Northern Territory Department of Plant Industries; University of Tasmania; Vic Forests, Victorian Department of Environment, Land, Water and Planning; and Western Australian Department of Biodiversity, Conservation, and Attractions.

Table 8 Exotic plantation species in tree improvement or breeding programs in Australia

Species	Agency
Pinus radiata *P. caribaea, P. elliotti* and hybrids	Forest Products Corporation, Forestry Corporation of New South Wales, Tree Breeding Australia and partners (including ForestrySA) HQPlantations, Queensland DAF
Khaya senegalensis	Queensland DAF
Santalum album	Queensland DAF, Quintis (not Australian provenances), Santanol

Tree breeding and improvement for forestry species has operated in Australia for a long time (**Table 9**). The first ornamental plantings of *Pinus radiata* were established around 1875 in South Australia, and their fast early growth prompted the state forest services of South Australia, Victoria and New South Wales to advocate plantations of this species to compensate for the relative paucity of native softwood in Australia (Wu et al. 2007). In southern Australia, formal *P. radiata* tree breeding commenced in the 1950s (Wu et al. 2007, Johnson et al. 2008). In Queensland, the *Araucaria* (hoop pine) breeding program commenced in the late 1940s, and the program for *Pinus caribaea* var. *hondurensis* commenced in the 1960s (Dieters et al. 2007; Nikles 1974; Nikles and Newton 1983a,b).

Table 9 Commencement of breeding programs for the main forest plantation species in Australia

Species	Commencement of formal breeding program	Source
Araucaria cunninghamii	Late 1940s (effectively on hold since 2007)	Dieters et al. 2007
Eucalyptus globulus *E. nitens*	Early 1970s First large-scale progeny trials established in the 1970s	Eldridge et al. 1993; Potts et al. 2014 Hamilton et al. 2008; Potts et al. 2014
Pinus caribaea var. *hondurensis* *P. radiata*	1960s 1950s	see Nikles 1974; Nikles and Newton 1983a,b Wu et al. 2007
Macadamia integrifolia and *M. tetraphylla*	1997	Topp 2019
Melaleuca alternifolia	1993	Shepherd and Mieog 2019

The long-term hoop pine breeding program captured substantial genetic gains in traits of economic importance, such as growth, stem straightness, internode length and spiral grain (Dieters et al. 2007). However, given organisational changes, limited funding for tree breeding, and the larger, higher priority *Pinus* plantation estate in Queensland, the hoop pine breeding program was placed on hold (Queensland DAF, pers. comm. 2021). Since 2006, there has been some loss of hoop pine clone banks and other genetic trials due to harvesting and bushfires. Recent genetic work on hoop pine has focused on deployment, and the establishment of a clonal seed orchard based on the best available selections for conservation purposes.

Breeding programs for *E. nitens* and *E. globulus* commenced in the 1970s (Hamilton et al. 2008; Eldridge et al. 1993; Potts et al. 2014) and up to three and four cycles of breeding, respectively, have since been completed (see **Appendix A**).

Eucalyptus globulus is the most widely planted commercial eucalypt species in Australia, and is mainly grown for pulpwood. Most of the Australian *E. globulus* plantations are in Western Australia and the Green Triangle region on the Victoria-South Australia border, which are outside of the natural range of the species (Barbour et al. 2008).

Eucalyptus nitens is the second most widely planted eucalypt species in Australia. It is mainly grown in Tasmania in regions where low temperatures (Tibbits and Hodge 1998) or *Teratosphaeria* leaf disease (formerly *Mycosphaerella*; Mohammed et al. 2003) limit the growth and survival of *E. globulus* (Potts et al. 2014). *Eucalyptus nitens* is mainly grown for pulpwood, but 27,000 hectares in Tasmania were managed for solid wood products in 2019-20 (ABARES unpublished data). Genetically improved seedlings are the main deployment propagule used for both *E. globulus* and *E. nitens* in Australia (Potts et al. 2008, 2014; Hamilton et al. 2008).

Across forestry species, the main traits selected for relate to survival after planting, growth (diameter, height, volume), pulp or sawn wood properties, and disease resistance. Depending on the species, other traits of interest are, or have been, susceptibility to wind damage, branching properties (*A. cunninghamii, P. radiata*), frost tolerance (e.g. *E. nitens*; Raymond et al. 1992, Byrne et al. 1997), reduced palatability to mammalian herbivores, and susceptibility to myrtle rust (e.g. Yong et al. 2019). Wood property traits under selection include cellulose content, pulp yield, lignin content, density, microfibril angle, wood stiffness (e.g. Thumma et al. 2010, 2015), compression wood, and spiral grain (Dieters et al. 2007).

For example, selection traits for *E. nitens* include diameter at breast height, stem straightness, branch diameter, basic density, and shrinkage traits (Kube and Raymond 2001, Hamilton et al. 2004, Hamilton et al. 2008). For *E. globulus* grown for pulpwood, key selection traits have been volume production, wood density and pulp yield. Sawn timber products from *E. globulus* and *E. nitens* require a longer rotation time, and have associated market and production uncertainties, so selection has initially focused on generic traits such as adaptability and form (Potts et al. 2014). For *P. radiata*, a major focus has been on wood properties, and breaking the adverse correlation between growth and strength.

Tree breeding has achieved significant gains for Australia's main plantation species. However, estimates of genetic gain through breeding have not been routinely published (e.g. Hamilton et al. 2008). Potts et al. (2014) noted that large gains for *E. globulus* were made in the 1990s, simply through sourcing open-pollinated seed from superior native stands identified in analyses of base population trials. Further economic gain can be captured through using breeding values to thin base-population progeny trials and create open pollinated seed orchards, using selected germplasm in open-pollinated seedling or grafted seed orchards, or using seed orchard or mass supplementary pollinated seed (Potts et al. 2008).

Table 10 shows the number of provenance, progeny and clonal trials under active management for key native species in plantations in Australia. **Appendix A** and **Appendix B** provide specific data for the FAO list of forest tree and woody plant species for Australia.

9.3.1 Tree breeding organisations

There has been a shift in the organisations involved in tree breeding for forestry in Australia. Several decades ago, CSIRO and state agencies conducted the majority of tree breeding. However, a significant amount of the tree breeding has transferred to the private sector, and a range of private companies now operate tree breeding programs for key timber tree species. **Table 7** shows the organisations involved in native species tree breeding in Australia.

Research and commercial collaborations such as Tree Breeding Australia (previously Southern Tree Breeding Association) allow companies to share resources to evaluate germplasm, introduce new traits into breeding material, and produce new selections. Tree Breeding Australia was formed in 1983, and runs cooperative national tree improvement programs for *Pinus radiata* and southern blue gum (*Eucalyptus globulus*), and provides database and quantitative analytical services for shining gum (*E. nitens*) and other plantation species.

Table 10 Tree improvement trials for main native species in Australia (trials under active management)

Species	Plus trees [a]	Provenance trials		Progeny trials		Clonal testing and development	
		No. of trials	No. of provenances	No. of trials	No. of families	No. of tests	No. of clones tested
Araucaria cunninghamii[b]	876 first-generation	20	50	~100	~900	–	–
Corymbia hybrids	0	-	-	20	500	15	30
C. citriodora	n.a.	3*	~15	3*	~80	-	-
C. maculata	n.a.	7*	15	7*	150	-	-
Eucalyptus cloeziana	25	-	-	1	-	1	-
E. dunnii	100	-	-	8	467	-	-
E. globulus	n.a.	92	>29	149	~7721	6	120
E. grandis	115	-	40	-	-	-	-
Eucalyptus hybrids	n.a.	4	-	3	154	-	-
E. nitens	n.a.	4	3	55	3351	-	-
E. pilularis	352	-	-	2	300	-	-
E. polybractea	200	>3	>27	7	~356	1	12
E. smithii	-	3	-	6	~400	0	0
Santalum album[c]	-	1	>1	5	120	-	-
S. lanceolatum	-	2	-	-	30	-	-
S. spicatum	-	1	6	1	100	-	-

—, not available; n.a., not applicable; *, combined provenance-progeny trial listed under both headings
This table shows the main species in tree improvement programs as at December 2020 for which trial data are available.
[a] Number of plus trees (superior trees) listed if program is beginning and only first-generation seed orchards have been established, or if the program is ending and only plus trees are retained.
Source: Status as at December 2020, based on consultation with organisations listed in **Table 7 as** well as Tree Breeding Australia and the Western Australian Department of Biodiversity, Conservation and Attractions;
[b] The breeding program for *Araucaria cunninghamii* is on hold. Data are from SOFR 2018, to indicate the number of trials in existence.
[c] The number of trials for *Santalum album* is underestimated as it omits some private company activities.

CSIRO manages a range of tree breeding trials and seed orchards around Australia (**Table 7** and **Table 10**), and collaborates with several organisations on tree breeding projects. CSIRO has a long history of tree breeding and molecular genetic research on forestry species.

Various state forestry management agencies also maintain tree improvement programs.

The Queensland Department of Agriculture and Fisheries (QDAF) tree breeding and improvement research is focused on Gympie messmate (*Eucalyptus cloeziana*) and spotted gums (*Corymbia citriodora* subsp. *citriodora*, *Corymbia citriodora* subsp. *variegata*, *C. henryi* and *C. torelliana*), and on determining species susceptibility to myrtle rust[68]. QDAF manages a range of seed orchards for producing improved seeds of *Eucalyptus* and *Corymbia*. QDAF also maintains a small program for *Khaya senegalensis*. Also in Queensland, tree breeding undertaken by HQPlantations focuses on exotic subtropical pine species and hybrids, and managing hoop pine (*Araucaria cunninghamii*) seed orchards.

The focus of Forestry Corporation of New South Wales is on commercial plantation production, mainly *Pinus radiata*. Some Southern Pine species are also planted (*Pinus taeda*, *P. elliottii* and

[68] daf.qld.gov.au/business-priorities/forestry/research-development/case-studies/identifying-resistance

P. caribaea var. *hondurensis* x *P. elliottii* hybrid) using seed purchased from HQPlantations which conducts the breeding and improvement for these species. The Forestry Corporation of New South Wales also manages two seed orchards of blackbutt (*E. pilularis*) that have been retained from a previous tree improvement and breeding program.

Sustainable Timber Tasmania and its predecessors have maintained a shining gum (*E. nitens*) breeding program for 40 years (Hamilton et al. 2008), producing seed and seedlings, and are also a partner in the Tree Breeding Australia southern (Tasmanian) blue gum (*E. globulus*) breeding program. Forico also manages a breeding program for *E. nitens* in Tasmania.

The main focus of ForestrySA is commercial *P. radiata* plantations. In partnership with Tree Breeding Australia, ForestrySA is establishing a genetic gains trial with the objective of identifying progeny best suited to drier areas (ForestrySA 2021). The Department of Primary Industries and Regions SA (PIRSA) also manages some species trials.

In Western Australia, the Forest Products Commission conducts tree breeding on pine species, and has recently established a *Pinus radiata* seed orchard, breeding trial and clonal archive near Manjimup, Western Australia.

Sandalwood plantations in Australia comprise Indian sandalwood (*Santalum album*, a native species, but the plantations have been established with provenances from India, Timor and Indonesia) and, more recently, the native species Australian sandalwood (*S. spicatum*). Seed of *S. spicatum* is harvested from native stands and increasingly from cultivated stands in the Western Australian wheatbelt[69] (see also **Table 4**). Tree breeding work aims to improve selections of sandalwood for productivity and oil yield. The Forest Products Commission is working on *S. spicatum*; Quintis (a private company) and the University of the Sunshine Coast have a small project on sandalwood in Queensland (*S. album* and *S. lanceolatum*); and Santanol (a private company) runs its own program.

The Western Australian Department of Biodiversity, Conservation, and Attractions owns seed orchards for blue-leaved mallee (*E. polybractea*) and York gum (*E. loxophleba* subsp. *lissophloia*), although the breeding programs for these species established by the predecessor Department of Conservation and Land Management have been closed. Work on blue-leaved mallee selections for improved oil production (**Table 4**, **Table 6** and **Table 7**) is being carried out by private industry in New South Wales and Victoria.

In the Northern Territory, the government work on forest tree species breeding and selection ceased in 2012. Work on African mahogany (*Khaya senegalensis*) was undertaken in collaboration with Queensland researchers (e.g. Nikles et al. 2008, 2014).

Other organisations that support research and collaboration in tree breeding and improvement in Australia include Forest and Wood Products Australia, and universities. Forest and Wood Products Australia has funded a range of projects on tree breeding[70], including the Eucalypt Sources for Timber Research database which contains information on eucalypt species trials in Australia with known genetic and silvicultural history and that have potential for future research related to solid wood processing and products (Cunningham et al. 2006).

Universities are also involved in species characterisation, provenance trials and other research to support tree breeding and revegetation projects, especially relating to climate change adaptability.

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[69] sandalwood.org.au

[70] fwpa.com.au/tag-search/tree-breeding.html

9.3.2 Current and emerging technologies

Tree breeding in the forestry sector has historically used traditional methods of field evaluation, phenotypic selections, cross-pollination, progeny evaluation, and cycles of breeding and selection based on quantitative genetic methods.

Over the past two to three decades, however, research using molecular techniques has increasingly informed tree breeding, including helping to determine genetic variation, identify suites of genes associated with traits of interest, reconstruct and manage pedigrees, and inform selections through integrating genomic relatedness into traditional quantitative methodologies (e.g. Moran 1992, Byrne et al. 1995, Butcher and Southerton 2007, Hamilton et al. 2008, Thumma et al. 2010). In some cases, marker-assisted selection could help reduce breeding cycles and reduce the number of progeny trials needed for estimation of traditional breeding values (Thumma et al. 2010, 2015).

Quantitative Trait Locus studies in trees including eucalypts have identified markers associated with important commercial traits (Butcher and Southerton 2007) and improved understanding of the genetic control of complex traits (Thumma et al. 2010). The development of high-throughput genomics has facilitated marker discovery approaches that are population-based, rather than pedigree-based. For example, DNA markers have been used to identify allelic variation in genes which influence pulp yield in *E. nitens*, and high-value wood and growth traits in *E. globulus* and *E. nitens*. These markers can be used to identify inferior genotypes in existing clonal orchards and screen new material for inclusion in future generations (Thumma et al. 2010, 2015). Marker-assisted selection has been shown promise in selecting superior lines of both *E. nitens* and *E. globulus* for rapid screening of seedlings for favourable traits such as density, pulp yield and growth (Thavamanikumar et al. 2018)[71].

Quantitative genetic techniques continue to be used for analyses of traits, selections and genotype-by-environment interactions. Integration of molecular and phenotypic data is now increasingly possible (e.g. Cappa et al. 2013, Bird et al. 2021), and is a major focus of Tree Breeding Australia.

The sophistication of techniques has improved over time, including due to decreasing cost of genotyping and sequencing, and increased capacity to process the 'big data' associated with integrated phenotypic and molecular data and carry out quantitative genetic analysis of traits and selections (e.g. with the TREEPLAN software used by Tree Breeding Australia).

Tree Breeding Australia uses an online database DATAPLAN®[72] to store and record all tree improvement information (including pedigree, various performance measurements and trial information) on its programs and those of its associates. This database is linked to the TREEPLAN® genetic evaluation system[73], which analyses tree improvement data collected across Australia to progress the quality of the genetic material used in industrial plantations (Kerr et al. 2001). TREEPLAN is used to update genetic values for *P. radiata, E. globulus* and *E. nitens*. State government organisations in Queensland and Western Australia also have well-developed databases of comprehensive trial information, including tree pedigrees and measurement data.

[71] forico.com.au/news/the-science-of-growing-better-trees
[72] stba.com.au/technology/dataplan
[73] stba.com.au/technology/treeplan

New technologies support tree breeding through trait measurement, such as near-infrared reflectance spectroscopy (NIR) to analyse selections for wood qualities; aerial and LiDAR imaging especially for disease traits; and trials of alternative grafted rootstock for macadamia.

9.3.3 Supply of reproductive material (forestry species)

Table 4 lists the main native plantation species for which seed is available as at December 2020. Seed is available from the Australian Tree Seed Centre (ATSC), various organisations and private collectors (e.g. Seed Energy) (see **Chapter 8**). Most wild seed is collected from native forests, with some restrictions on collection of seed from wild population. Improved seed is collected from pedigreed seed orchards and seed production stands. There are many commercial nurseries that supply seedlings for the forestry industry.

9.4 Tree breeding – macadamia

Macadamia are native Australian trees, with two species used in plantations for production of macadamia nuts in Australia and overseas. The main species grown in Australia is *Macadamia integrifolia*, with smaller numbers of *M. tetraphylla* and hybrids.

Macadamia breeding commenced in Australia with a trial field planting in 1997-1998, from which elite accessions were selected and planted into regional trials (Topp 2019). First-generation progeny were planted into trials from 2001-2003, from which further elite accessions were selected and propagated for inclusion in a series of regional variety trials. The breeding program is currently making selections from the second generation to make the third generation.

Commercial macadamia species have a long juvenile period, so breeding new varieties is a slow process. Selection criteria have been tree height, trunk circumference, nut size, shell thickness and kernel recovery, yield and yield stability. Priority traits for growers include high nut-in-shell yield per tree, small tree size, high kernel recovery, precocious fruiting, and resistance to husk spot and other pests and diseases (Topp 2019). There have been significant gains in macadamia nut quality and production through the breeding program.

Much of the world's commercial plantation stock is based on a small number of original trees (see Macadamia case study in **Chapter 7**), so a goal of Australia's breeding programs has been to increase the genetic base for selection. The National Macadamia Germplasm Collection provides information on wild genetic diversity and population structure. Wild germplasm is an important source of genetic diversity for the macadamia breeding program, through introducing new accessions of *M. integrifolia* and *M. tetraphylla* into the breeding program. Trees of *M. ternifolia* and *M. jansenii* are much smaller and could contribute desired size phenotypes through cross-pollination. Wild germplasm may also have resistance to pathogens.

9.4.1 Organisations involved

Macadamia breeding commenced with government agencies (CSIRO, QDAF and its predecessors), funded by industry. Australian tree breeding for macadamia is currently conducted by the Queensland Alliance for Agriculture and Food Innovation (QAAFI) at The University of Queensland, funded by Horticulture Innovation Australia, as well as by private companies.

9.4.2 Technologies and supporting research

Priorities for future breeding work in macadamia (Topp 2019) include continuing to increase progeny field trial population sizes; improving methods for efficiently selecting multiple traits; continuing to breed for grower-defined priority traits and traits that allow for improved harvesting efficiency and easier tree management; and incorporating genomic selection tools to increase breeding efficiency.

Current research projects and technologies assisting the tree breeding program include looking for genetic markers related to traits of interest, investigating the population structure and genetic diversity of the breeding program, and investigating genetic (family) resistance to husk spot (*Pseudocercospora macadamiae*), which can cause premature fruit abscission.

9.4.3 Availability of reproductive material

The Australian Macadamia Society[74] provides information to growers on a range of topics including available varieties and rootstock. The supply of varieties and grafted stock is undertaken by commercial companies and nurseries.

9.5 Tree breeding – tea tree

Tea tree oil is distilled from the leaves of *Melaleuca alternifolia* for use in a range of healthcare, cosmetic, pharmaceutical and veterinary products (Carson et al. 2006; RIRDC 2013, 2018; Shepherd and Mieog 2019). The oil is rich in terpenoid compounds.

Melaleuca alternifolia is endemic to coastal areas of subtropical eastern Australia. Much original habitat has been cleared for agriculture and urban settlement, but the species is conserved in situ in parks and reserves. *Melaleuca alternifolia* is also cultivated in plantations in Brazil, China, Indonesia, Kenya, Madagascar, Malaysia, South Africa, Tanzania, Thailand, United States, and Zimbabwe (Silva et al. 2007; RIRDC 2013; Bejar 2017; Larkman T, Australian Tea Tree Industry Association, pers. comm. 2021).

Over the past 30 years, production of tea tree oil in Australia has changed from hand harvesting in native forest stands to a fully mechanised plantation-based industry. The plantation estate in Australia is about 4500 hectares. The entire above-ground shoot biomass is harvested and steam-distilled to produce a purified essential oil.

The Australian tea tree breeding program commenced in 1993, focussing on increases in oil yield and quality, and has increased oil yields about three-fold (Shepherd and Mieog 2019). A small elite population was established in 2018, selected from elite trees identified in the third-generation breeding population, and is subject to controlled pollination and full pedigree control. The breeding program is also progressing a larger main population by open pollination, to provide a low-risk source of improved seed and a broad genetic base for future selection. Ex situ conservation includes more than 40 legacy genetics trials, orchards and clonal archives.

Genome sequencing of *M. alternifolia* (Calvert et al. 2017; Voelker et al. 2021) and molecular genetic analysis (Keszei et al. 2010, Padovan et al. 2017a) have identified genes and gene variants contributing to higher oil yield and terpene composition, and offer the potential to accelerate the breeding program. The development of genetic markers for tea tree has facilitated assessment of wild and cultivated populations, and monitoring genetic diversity during domestication and deployment (Rossetto et al. 1999a,b; Voelker and Shepherd 2020). The related *M. linariifolia*, also permitted under ISO 4730 for use as tea tree oil, is tolerant to a wider range of environmental conditions and may be useful in expanding the genetic resource for breeding and production (Brophy et al. 2013).

[74] australianmacadamias.org/industry

9.5.1 Organisations involved

The tea tree breeding program was initially led by the New South Wales Department of Primary Industries (DPI) and CSIRO. In 2017, the program transitioned to Southern Cross University, which is conducting the program on behalf of the Australian Tea Tree Industry Association, a not-for-profit industry representative body.

9.5.2 Supporting research

Recent research supporting the tea tree breeding program has included investigating cultivars low in methyl eugenol, the diversity of terpene chemotypes, commercially viable clonal propagation, and rapid phenotyping of oil content and composition (Shepherd and Mieog 2019).

9.5.3 Availability of seed

Commercial seed is processed and stored at Southern Cross University, which manages new collections and the dispatching of production seed to growers and propagators (Shepherd and Mieog 2019).

9.6 Tree breeding – lemon myrtle

Backhousia citriodora (lemon myrtle) is native to subtropical and tropical rainforests of coastal Queensland, and is grown in plantations for its leaves, which contain an oil rich in citral (lemon-scented essential oil: House et al. 1996; Southwell 2021). Dried leaves and the oil are used as a flavour and fragrance and for antibacterial and antifungal properties. The current estimated farm gate value is $12.2 million, and this has been predicted to double in the next five years (Laurie 2020).

Plantations have been based on unselected material, often of unknown origin. Early family and provenance trials in south-east Queensland established from range-wide collections showed significant variation in both growth and oil characteristics, providing scope for selection and mass propagation of superior families and clones (House et al. 1996).

The genetic base of *B. citriodora* is susceptible to *Puccinia psidii*, which causes myrtle rust (Lee et al. 2016). However, there is significant provenance variation in resistance to myrtle rust (Doran et al. 2012), suggesting the possibility of selecting cultivars with greater tolerance to the disease. A representative genetic pool of varieties was established at three sites, but the status of two of these plantings is unclear (Lee D, University of Sunshine Coast, pers. comm., 2021).

9.7 Needs, challenges and opportunities for tree improvement and breeding

The needs and challenges for forest tree improvement and breeding in Australia are:

- ensuring ongoing access to in situ genetic material, and protecting in situ and ex situ material from risks such as introduced diseases, land-use change and bushfire
- ongoing breeding and improvement of commercial plantation species to help industries adapt to changes in markets, products and climate
- integrating tree breeding with product evaluation and development
- monitoring the susceptibility of eucalypt and tea tree species and varieties to myrtle rust
- evaluating key plantation and threatened species for climate change adaptability
- access to overseas genetic material, especially for pines.

Research is currently underway to select forest tree genotypes adapted to projected warmer and drier conditions, and resistant or tolerant to potential increases in the numbers and severity of pests, diseases and weeds associated with climate change (e.g. Bush et al. 2018).

Myrtle rust remains a challenge for many commercial species (see **Chapter 2**). Modelling based solely on the climatic component of the potential risk of myrtle rust has suggested that a significant area of existing eucalypt plantations may be affected (Singh et al. 2016). Currently that threat has not been realised, but there is clear opportunity for incorporation of resistance or resilience to myrtle rust into selection and breeding programs.

Opportunities for tree improvement include:

- further collaboration on tree breeding
- more rapid breeding with the assistance of molecular marker-based techniques
- improvement of new species
- improving plantation material using wild genetic material.

9.8 Priorities for capacity-building and research

Priorities for capacity-building include:

- training and employment opportunities in tree breeding
- developing more reliable and cheap phenotyping methods for key traits, such as oil content determination in tea tree and sandalwood
- aerial data gathering for disease monitoring and other purposes to assist forest genetic resource management and tree breeding and improvement.

Priorities for research include:

- further development of molecular techniques such as genome mapping, genomic relatedness and marker-associated selection, to facilitate faster selection and breeding
- integrating breeding with product evaluation and development
- monitoring the susceptibility of eucalypt species and tea tree varieties to myrtle rust, and selecting genetic material that is less susceptible
- evaluating key plantation and threatened species for climate change adaptability.

10 Management of forest genetic resources

10.1 Key points

- Genetic considerations are taken into account in management of native forests for conservation and for production, and in management of plantations.
    - Genetic concerns are an input into decision-making about areas to incorporate in reserve systems, and were included in Comprehensive Resource Assessments for conservation areas within Regional Forest Agreements.
    - Genetic information is considered (where available) in listing and management of threatened species. This includes genetic-related threats due to small or fragmented populations, low genetic diversity or fecundity issues.
    - Locally sourced seed or saplings are used routinely as a genetic resource conservation mechanism during native forest regeneration after harvesting.
    - Many different parameters under genetic control have been incorporated into breeding programs for plantation species, including growth rate, wood properties, branching patterns, and pest resistance.
- Technologies relating to management of forest genetic resources include:
    - micropropagation and clonal propagation of threatened species
    - spatial modelling of risks to native forests and plantations from climate change and pest incursions
    - use of molecular markers and genomics to accelerate breeding programs.
- Trends in management of forest genetic resources include:
    - provenance selection for future climates for commercial species and conservation plantings
    - provenance selection for management of areas of eucalypt species experiencing dieback (for example snow gum, manna gum and cider gum)
    - mapping fire impacts on threatened species.
- Needs, challenges and opportunities for improving the management of forest genetic resources include further improvement to propagation methods for threatened species, and identification of provenances of forest trees more suited to future climates.
- Research priorities include methods for rapid analysis of genetic variation within forest species, and investigation of the genetic basis of complex characters important for plantation productivity.

10.2 Genetic considerations during forest management

10.2.1 Forest reservation and threatened species assessment

The Convention on Biological Diversity is an international treaty that links sustainable economic development with the preservation of ecosystems, species and genetic resources. Genetic concerns with individual species have therefore been an input into decision-making about areas to incorporate in the National Reserve System, and were also included in Comprehensive Resource Assessments for conservation areas within Regional Forest Agreements.

The number of forest-dwelling native fauna and flora for which data on genetic variation are available is still small. However, available genetic information is considered in listing and management of individual threatened species. Genetic-related criteria include low population size, populations comprising only a few subpopulations, fragmented populations, low measured genetic diversity, occurrence of hybridisation, and fecundity issues.

Of the 1,075 forest flora species listed as threatened under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), 747 species (69%) had one or more genetic-related reasons associated with their listing (MIG and NFISC 2018). Long-term genetic conservation outcomes can be improved by placing seed of threatened flora species into seed banks, and by increasing connectivity among patches of native vegetation.

Harvest of seeds and other reproductive material from native forests (both in formal reserves and multiple-use native forests) is monitored by Australian, state and territory government agencies responsible for natural resource management, using permit systems.

10.2.2 Management of forests

The Australian Forestry Standard and the Forest Stewardship Standard of Australia both set requirements to protect and maintain the elements of the biological diversity of forests, including genetic diversity. For example, the Australian Forestry Standard Limited 2013[75] requires that:

- "…forest operations … provide adequate genetic, species and structural diversity"
- "The forest manager shall regenerate native vegetation with species and provenances native to the area, or from an equivalent locality, as far as reasonably practicable, to maintain local gene pools and species mixes."
- "The forest manager shall manage plantations to develop and implement strategies to minimize the risk and consequences of genetic pollution from pollen flow between plantations and native forest species. The strategies will consider the conservation status of any adjacent forest ecosystem or gene pool, the probability that pollen-mediated gene flow will occur, and the impact that such gene flow is likely to have on any adjacent population or forest ecosystem."

Maintenance of genetic diversity as a management goal also features in legislation, regulation and codes of practice for native forest management, with which private sector forest managers, government agencies and research organisations must comply.

Natural regeneration is often used to regenerate native forests after timber harvesting. This can involve relying on soil seed, or retaining advanced growth saplings, or retaining 'seed trees' to allow seed fall from their retained canopy. Fire is used in certain forest types to assist seed release, provide a seed-bed or stimulate germination. All these management approaches use the on-site genetic stock as the basis for the regenerating forest.

At times, however, regeneration is assisted in harvested native forest. In those circumstances, forest managers use locally sourced seed or seedlings. For example:

- in Tasmania, Sustainable Timber Tasmania collects eucalypt seed from areas to be harvested and adjacent. Seed is sown after harvest in volume ratios guided by the species mix of the pre-harvest stand. Seed sown at a site must come from areas within the same 'seed zone', to maximise the likelihood of the regenerating forest being

[75] responsiblewood.org.au/wp-content/uploads/2017/11/AS4708-2013-Publish.pdf

genetically adapted to the local climate and site condition areas (Forestry Tasmania 2010). Seed zones have been recently updated[76].

- in Western Australia, the Forest Products Commission sow 10-20 tonnes of seed of *Santalum spicatum* (Australian sandalwood) annually to regenerate harvested areas in the rangelands (Brand J, Forest Products Commission, pers. comm. 2021)
- after native forest harvesting, the Forest Products Commission also plant seedlings of karri (*Eucalyptus diversicolor*) that have been germinated from locally sourced seed[77]. Regeneration survival is monitored after the first summer following establishment; if survival is not sufficient, in-fill planting is done the following winter.

10.2.3 Plantation establishment and management

Genetic considerations are central to the choice of stock used for establishment of plantations, or their re-establishment after harvesting, as covered in **Chapter 9**. Many different parameters under genetic control have been incorporated into breeding programs, including growth rate, wood properties, branching patterns, and pest resistance. Consideration of genetic-by-environment interactions leads to selection of different genetic lines for sites of different quality. Current developments include selection for provenances suitable to future climates.

The need for plantation management to minimise the potential for gene flow from plantations to adjacent native forest through hybridisation is explained in **Chapter 5**.

10.3 Current and emerging technologies

Technologies relating to management of forest genetic resources include:

- micropropagation and clonal propagation. For example, extensive clonal propagation of Wollemi pine (*Wollemia nobilis*) following its discovery has been undertaken through cuttings (see Pohio et al. 2005) as part of conservation of this unique species[78].
  The conservation biotechnology program at Kings Park and Botanic Garden, Western Australia[79], develops new in vitro propagation methods for threatened plant species for off-site conservation and translocation, including tissue culture, micropropagation, somatic embryogenesis and cryostorage
- the increased use of spatial modelling of risks to native forests and plantations from climate change, fire threats and pest incursions
- implementation of molecular and genomic approaches to accelerate breeding programs, as described in **Chapter 9**.

10.4 Trends, changes and threats for management of forest genetic resources

As well as an increased use of molecular data to accelerate selection for desired traits in plantation species, trends in management of forest genetic resources include an increased focus on selection for climate change adaptation through the use of planting stock more suitable for future climates, and developing capacity to undertake fire risk mapping for threatened species.

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[76] media.utas.edu.au/general-news/all-news/new-seed-zones-adopted-by-industry
[77] wa.gov.au/organisation/forest-products-commission/karri-forest-regeneration
[78] rbgsyd.nsw.gov.au/Science/Our-work-discoveries/Germplasm-Conservation-Horticulture/Wollemi-Pine-Conservation-Program
[79] bgpa.wa.gov.au/kings-park/events/research/conservation-biotechnology

10.4.1 Climate change adaptation

Climate change is predicted to lead to changes in temperature and rainfall, and increased frequency and intensity of both drought and fire. Species will likely change in genetic diversity and distribution as they respond and adapt to climate change.

For example, *Fontainea rostrata* is a threatened dioecious rainforest tree of the subtropical notophyll vine forests of eastern Australia. Conroy et al. (2019) found differences in regional genetic parameters between the main populations in the south and a disjunct northern population cluster. Species distribution models predicted that, while southern populations of *F. rostrata* are likely to persist for the next 50 years under the modelled climate change scenario, the more highly inbred and less genetically diverse northern populations will come under increasing pressure to expand southwards as habitat suitability declines. The authors recommended maximising the species genetic diversity and likelihood of reproductive success through plant reintroductions to supplement existing populations, then future translocation to establish new sites in habitat identified as persisting under climate change.

Debate about assisted migration and assisted gene flow in forest trees is ongoing, as it is possible that at least for some species, naturally occurring long-distance gene flow may be enough to facilitate rapid natural adaptation to climate change (Larcombe et al. 2016). However, eucalypts have poor dispersal capabilities, and it is expected that, rather than moving with changing climate, the adaptive capacity of eucalypts will determine survival in their current location (Booth et al. 2015). Consideration of the genetic variability of three widespread eucalypts (*Eucalyptus salubris*, *E. tricarpa* and *E. loxophleba* subsp. *lissophloia*) led to the conclusion that these species are likely to have some capacity to respond plastically to a changing climate. However, selection of revegetation seed sources to match projected climate changes may confer greater climate resilience (Byrne et al. 2013; Prober et al. 2015, 2016).

Current forest genetic resources are thus now being used to select tree genotypes with traits that are resistant or tolerant to projected warmer and drier conditions and potential increases in numbers and severity of pests, diseases and weeds associated with climate change. Australian researchers are also working on provenance selection suited to future climate-change scenarios, through informing seed collection for biodiversity plantings, using 'climate-adjusted provenancing' (Prober et al. 2015). For example, the University of Tasmania and Greening Australia have planted provenance trials of cabbage gum or snowgum (*E. pauciflora*) and black gum or swamp gum (*E. ovata*) in Tasmania to test their suitability for future climate change scenarios (Prober et al. 2016).

Greening Australia is currently working with university researchers on provenance selection suited to future climate change scenarios, to inform seed collection for biodiversity plantings. For example, Greening Australia is collaborating with CSIRO on developing a climate-adjusted provenance mix for revegetation, using direct-seeding trials at three sites on the New South Wales southern tablelands[80], and planting provenance trials of *E. viminalis*. A long-term trial at the Bush Heritage Australia reserve at Nardoo Hills, Victoria, in alliance with Greenfleet is testing revegetation with climate-adjusted provenance seed[81].

Future integrated management of forests against stressors will increasingly incorporate research-based genetic selection for species or provenances able to cope with more extreme climatic conditions, and to mitigate dieback events. An example is identification of species or

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[80] greeningaustralia.org.au/our-research-partners/
[81] bushheritage.org.au/projects/nardoo-climate-ready-revegetation

provenances resistant or resilient to climate-driven dieback, drought and insect attack, as is occurring in high-altitude forests of snow gum (*E. pauciflora*) of the Australian alps in New South Wales and Victoria, manna gum (*E. viminalis*) on the Monaro high plains in New South Wales, and cider gums (*E. gunnii*) in Tasmania[82,83,84] (Ross and Brack 2015). Research on the issue includes investigation of provenances of these species more resistant to drought and high temperatures for potential use in forest restoration.

10.4.2 Fire

Fire is a natural part of Australia's ecology, but drought and climate change affect fire regimes, and contribute to greater fire extent, frequency and intensity.

In the Australian 2019-2020 bushfire season, known as the 'Black Summer', bushfires in southern and eastern Australia were unusually extensive following an extended drought. In total, these bushfires burnt 10.3 million hectares of land including 8.5 million hectares of forest[85]. Following these fires, the Australian government undertook prioritisation exercises to identify animal species, plant species and threatened ecological communities that required rapid management intervention[86], and identified 486 plant species in this category[87] based on a suite of 11 prioritisation criteria applied across 26,062 plant taxa (Gallagher 2020).

The effect of these fires on the species on the FAO list of forest genetic resources for Australia varied. Of the 129 forest species and hybrids currently on the FAO list of forest genetic resources for Australia, three are on the priority list for urgent action following the 2019-2020 bushfires, *Eucalyptus gunnii, E. remota* and *Wollemia nobilis*. For *Macadamia jansenii*, which has a population of 200 individuals, 25% of its known distribution was burned in these fires; some individuals are coppicing, but the long-term effect on the species is yet to be determined (Bond D, Australian Macadamia Society pers. comm. 2021).

The Australian Seed Bank Partnership is delivering projects to collect data on species recovery post-fire, to inform future bushfire response from conservation practitioners and land managers[88]. Projects focus on genetically diverse seed collections as an insurance policy, collecting from multiple populations across a species range to capture its genetic diversity. Securing genetically diverse collections can conserve new and novel genes that could help a species survive future threats such as climate change, pests and disease.

10.5 Needs, challenges and opportunities

As outlined in **Chapter 6**, under future climate change scenarios Australia's National Reserve System may be less effective at protecting species (Williams et al. 2016). Needs, challenges and opportunities for improving the management of forest genetic resources include:

- further improvement to propagation methods for threatened species
- identification of provenances of forest trees more suited to future climates
- work on the acceptability of translocation of provenances or species to other areas.

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[82] theguardian.com/environment/2021/mar/10/hopes-nsw-grant-of-12m-will-open-door-to-finding-cause-of-eucalypt-dieback
[83] abc.net.au/news/2021-03-10/sudden-death-of-snow-gums-longicorn-beetle/13226128
[84] tasland.org.au/blog/from-the-field-cider-gum-recovery/
[85] awe.gov.au/abares/forestsaustralia/forest-data-maps-and-tools/fire-data
[86] awe.gov.au/environment/biodiversity/bushfire-recovery/bushfire-impacts
[87] awe.gov.au/environment/biodiversity/bushfire-recovery/bushfire-impacts/priority-plants
[88] seedpartnership.org.au/initiatives/bushfire-recovery/

11 Institutional framework for conservation, use and development of forest genetic resources

11.1 Key points

- Australia does not have a formal national coordination mechanism on forest genetic resources. However, Australia's main mechanism for conservation of forest genetic resources, *in situ* conservation, is coordinated nationally through Australian, state and territory government cooperation on the National Reserve System.
    - The Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* allows for listing and protection of species and ecological communities identified as threatened. Each state and territory also has legislation to protect and conserve biodiversity, designate conservation reserves, and list and prepare recovery plans to manage threatened species. Each state also has legislation to restrict land clearing and to manage harvest from native forests.
    - *Australia's Strategy for Nature 2019-2030* is Australia's national strategy for conservation and sustainable (use and) management of nature. The Australian Government's *Threatened Species Strategy 2021-31* outlines an action-based approach to protecting and recovering the nation's threatened plants and animals.
    - Sustainable use and development of forest genetic resources in major commercial forestry regions of Australia is addressed through Regional Forest Agreements. There are also government codes of practice and legislation for native forest management, and for use and benefit sharing of forest genetic resources.
- The *Biosecurity Act 2015,* the *Export Control Act 1982* and state and territory legislation provide protection against the introduction and spread of pests, diseases and weeds by regulating movement of forest genetic resources and other biological materials.
- The main national inventory of forest genetic resources is the *Australia's State of the Forests* Report (SOFR) series, which is produced every five years and includes a national summary of the conservation status of forest genetic resources and research and development efforts.
- There is no coordinated extension program for forest genetic resources. However, within the forestry industry, collaboration and partnerships allow sharing of some forest genetic resource information. Also, relevant information on forest genetic resources, such as for provenance selection, is provided to landholders involved in revegetation projects on a project-by-project basis.
- There are opportunities for greater coordination of institutions and resources, and to continue to include genetic resource conservation issues in action plans for threatened species, and to include forest refugia in priority places for conservation planning.

11.2 Australian government responsibilities

Australia includes six states and three mainland territories. The powers and responsibilities of the Commonwealth government are defined in the Australian Constitution. Land management responsibilities rest with the states and territories, as does most environmental legislation, although the Commonwealth has substantial powers to enact laws affecting the environment and sustainable development.

There are shared responsibilities between the Australian and state or territory governments in some matters relating to agriculture, forestry and biological diversity. Australian states and territories have legislation in place for conserving native vegetation, including regulations on land clearing. Examples of relevant legislation are provided in **Table 11**.

11.3 Conservation legislation and policy

11.3.1 Environment protection legislation

The Australian Government Department of Agriculture, Water and the Environment is responsible for implementing the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), which is the Australian Government's main piece of environment legislation. It allows for designation of conservation reserves on Commonwealth land, and for assessing, listing and protecting species and ecological communities identified as threatened nationally. The Act also allows for the formal recognition of key threatening processes that impact native plants and animals. Once listed under the Act, private and public entities are then required to consider threatened species and ecological communities within their operations and, if threatened species and ecological communities may be significantly impacted, refer their action to the environment minister for assessment and approval.

The threatened species assessment process under the EPBC Act includes criteria to consider the threats, trends in population size and distribution of species. Many of the species listed as threatened have small populations or are at risk of loss of genetic diversity, partly due to land clearing and a high level of species endemism in Australia. The EPBC Act mechanisms provide a framework from which regional approaches to recovery and other conservation planning activities can be developed and implemented.

11.3.2 Sub-national strategies

Each state and territory also has legislation to protect and conserve biodiversity, designate conservation reserves, and list threatened species and prepare recovery plans to manage threatened species. As for the national legislation, their focus is on managing the various threats to biodiversity, improving vegetation connectivity, and maintaining and enhancing the system of protected areas.

Some state and territory strategies also address conservation and use of genetic resources. For example, the *Protecting Victoria's Environment – Biodiversity 2037*[89] strategy has five key goals including to improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity. Actions include:

- increasing habitat quality and extent, creating additional habitat areas and connections
- enhancing biodiversity by directly managing native species though actions such as translocations and genetic strengthening. An example is fire-hardy replacements for alpine ash (*Eucalyptus delegatensis*) in wet forests.

Some strategies, such as the *Threatened Species Strategy for Tasmania*[90], aim to maintain and build ex situ populations of plants and animals vulnerable to loss from climate change.

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[89] environment.vic.gov.au/biodiversity/biodiversity-plan
[90] dpipwe.tas.gov.au/Documents/threatspstrat.pdf

Table 11 Domestic legislation relevant to forest genetic resources

Jurisdiction	Legislation
Commonwealth	*Aboriginal and Torres Strait Islander Heritage Protection Act 1984* *Native Title Act 1993* *Plant Breeder's Rights Act 1994* *Environmental Protection and Biodiversity Conservation Act 1999* [a] *Regional Forest Agreements Act 2002* [b] *Biosecurity Act 2015*
Australian Capital Territory	*Environment Protection Act 1997* *Plant Disease Act 2002* *Planning and Development Act 2007* *Public Unleased Land Act 2013* *Nature Conservation Act 2014*
New South Wales	*Plant Diseases Act 1924* *National Parks and Wildlife Act 1974* *Environmental Planning and Assessment Act 1979* *Native Vegetation Act 2003* *Biodiversity Conservation Act 2016*
Northern Territory	*Territory Parks and Wildlife Conservation Regulations 2001* *Biological Resources Act 2006* *Territory Parks and Wildlife Conservation Act 2006* *Plant Health Act 2008*
Queensland	*Forestry Act 1959* *Plant Protection Act 1989* *Nature Conservation Act 1992* *Vegetation Management Act 1999* *Biodiscovery Act 2004* *Vegetation Management and Other Legislation Amendment Act 2009*
South Australia	*Forestry Act 1950* *National Parks and Wildlife Act 1972* *Native Vegetation Act 1991* *Wilderness Protection Act 1992* *Plant Health Act 2009*
Tasmania	*Threatened Species Protection Act 1995* *Plant Quarantine Act 1997* *National Parks and Reserves Management Act 2002* *Nature Conservation Act 2002*
Victoria	*National Parks Act 1975* *Wildlife Act 1975* *Planning and Environment Act 1987* *Flora and Fauna Guarantee Act 1988* *Plant Health and Plant Products Act 1995* *Parks Victoria Act 2018*
Western Australia	*Soil and Land Conservation Act 1945* *Wildlife Conservation Act 1950* *Conservation and Land Management Act 1984* *Sandalwood Act 1999* *Biosecurity and Agriculture Management Act 2007*

[a] The Commonwealth *Environmental Protection and Biodiversity Conservation Act 1999* applies to all states and territories (including external territories).
[b] Applies to RFA regions in New South Wales, Tasmania, Victoria and Western Australia.

11.3.3 Threatened Species Strategy

The Australian Government's *Threatened Species Strategy 2021-31*[91] is its forward plan for action to protect and recover Australia's threatened plants, animals and ecological communities. It delivers a framework for protection and recovery of threatened plants and animals across Australia, identifies action areas fundamental to the recovery of threatened species and ecological communities, and establishes principles for identifying priority threatened species and places.

The strategy notes that the establishment of captive-bred populations and genome banks for threatened animals and seedbanks for threatened plants, complemented by wild-to-wild translocations and supported by the network of island and safe havens, help to reduce the risk of extinction from stochastic events as well as from climate change.

The previous *Threatened Species Strategy 2015-20* nominated 30 priority species, two of which are present in the FAO list of forest genetic resources for Australia, *Eucalyptus morrisbyi*[92] and *E. crenulata*[93].

11.4 Biosecurity

Australia's *Biosecurity Act 2015, Export Control Act 1982* and state and territory legislation provide protection against the introduction and spread of pests, diseases and weeds by regulating movement of forest genetic resources and other biological materials.

The *Quarantine Proclamation 1998* provides the legislative basis for controlling the entry of animals, plants and other goods of quarantine concern into Australia. Subsections 62 and 63(1) provides that importing living plants or seeds, with certain exceptions, is prohibited unless the Director of Quarantine has granted a permit.

Phytosanitary restrictions are imposed on imports of seeds and nursery stock of forest and woody plant species from certain countries of origin, including bans on high-risk imports. Australia's import conditions for forest genetic materials can be accessed from the Department of Agriculture, Water and the Environment's Biosecurity Import Conditions (BICON) database[94].

Within Australia, conditions can be imposed on the interstate or intrastate movement of forest genetic materials under state, territory or Commonwealth legislation to safeguard 'pest-free areas' against pest introduction, providing a pest meets the criteria of 'quarantine pest' as defined by the International Plant Protection Convention[95].

[91] awe.gov.au/environment/biodiversity/threatened/publications/threatened-species-strategy-2021-2031
[92] awe.gov.au/environment/biodiversity/threatened/species/30-plants-by-2020/morrisbys-gum
[93] awe.gov.au/environment/biodiversity/threatened/species/30-plants-by-2020/silver-gum
[94] awe.gov.au/import/online-services/bicon
[95] ippc.int/en/

11.5 Use and development of forest genetic resources

11.5.1 National forest policy

As outlined in **Chapter 6**, Australia's *National Forest Policy Statement*[96] commits the Australian, state and territory governments to maintain an extensive and permanent native forest estate, and to manage the native forest in an ecologically sustainable manner.

Regional Forest Agreements (RFAs) are a key element of Australia's forest management in four Australian states where commercial forestry is significant. At signing of the RFAs, Australia established a CAR reserve system based on principles of Comprehensiveness, Adequacy and Representativeness (CAR). Comprehensive regional assessments included consideration of genetic resources and resulted in the expansion of the reserve estate (Jacobsen et al. 2020).

Commonwealth, state and territory government legislation (**Table 11**) and policy is applied to manage harvest and use of native forest resources, and protection of threatened species.

11.5.2 Indigenous use

Some small-scale enterprises operated by or employing Indigenous people or communities are based on eco-tourism, 'bush tucker' (native foods), or timber harvesting. There is however currently no institutional framework to support development and use of forest genetic resources by Indigenous communities or for developing guidelines for sustainable harvest.

Kakadu plum is currently harvested from native forests and used commercially as a food, food preservative, and ingredient in cosmetics. The National Measurement Institute is currently working with the Northern Australia Aboriginal Kakadu Plum Alliance (NAAKPA) to test Kakadu plum and other native species for a range of qualities[97]. NAAKPA have also undertaken a pilot provenance and traceability project to develop a database of isotopic fingerprints of Kakadu plum harvested at key locations, with a view to trialling a system of traceability and verification for bush food supply chains[98].

11.6 Research and development

Universities, government, CSIRO, non-government organisations and private companies are involved in research and development on forestry, tree breeding, forest conservation and forest genetics (see **Chapter 9**; Singh et al. 2013). However, since 2007 capacity and expenditure on research and development in forestry sectors has declined progressively (MIG and NFISC 2018). The range of topics for forest research in Australia (MIG and NFISC 2018) includes:

- plantation species tree selection and breeding
- species/provenance adaptation to climate change
- genomics of native species
- conservation actions to maintain viable populations of target species in native forests and reserves, including via translocation.

Data on expenditure allocated to forest genetics research are not available, and are difficult to separate from other expenditure on forest and biodiversity research.

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[96] awe.gov.au/forestry/policies/forest-policy-statement
[97] industry.gov.au/news/support-for-the-northern-australia-aboriginal-kakadu-plum-alliance
[98] naakpa.com.au/indigenous-provenance-and-traceability-technology-platform; naakpa.com.au/samples-collect-for-isotopic-fingerprints ; smarttrademark.search.ipaustralia.gov.au/

11.7 Education and training

Employment in management of forests and forest genetic resources draws on people from a range of education and training backgrounds. Several university courses provide training in genetics, agriculture and forestry. Postgraduate studies provide an avenue for students to train in genetics of forest species, particularly where research projects provide funding.

There is no coordinated extension program for provenance selection or other aspects of forest genetic resources. However, within the forest industry, there is some exchange of genetic resource information through collaborative projects and partnerships. Some information is provided to landholders involved in revegetation projects on a project-by-project basis, via government conservation departments and environmental non-government organisations.

11.8 Needs, challenges and opportunities

There are opportunities to encourage greater coordination of institutions and resources in regards to research and management of forest genetic resources. There is also ongoing need to continue to include genetic resource conservation issues in action plans for threatened species, and to include forest refugia in priority places for conservation planning.

11.9 Priorities for capacity-building

There is ongoing need for training in forest genetics for conservation, tree breeding, climate-change adaptation, and sustainable harvest of forest genetic resources.

12 International and regional cooperation on forest genetic resources

12.1 Key points

- Australia is a party to international organisations, agreements, treaties, conventions and trade agreements that are directly or indirectly relevant to the conservation, sustainable use and development of forest genetic resources. These include the Convention on Biological Diversity, the International Tropical Timber Agreement, and the World Trade Organisation Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement).
  - Australia has signed, but not yet ratified, the Nagoya Protocol on Access and Benefit Sharing.
  - Australia also participates in a number of bilateral, multilateral, sub-regional and regional activities that are directly or indirectly related to forest genetic resources.
- The Forestry Program of the Australian Centre for International Agricultural Research (ACIAR) funds international collaborative projects that address priority development themes, including germplasm conservation, improvement and distribution, and forest restoration, management and protection.
- The benefits to Australia of international cooperation on forest genetic resources include improved capacity in Australian research institutions, improved knowledge of the performance of Australian eucalypts and acacias under different environmental conditions, techniques for growing sandalwood plantations, enhanced networks, and the opportunity to monitor biosecurity threats to forests and forestry, particularly in the Pacific region but also south-east Asia and eastern Africa.
- Needs, challenges and opportunities for international and regional cooperation on forest genetic resources include:
  - government, donor and private sector partnerships to expand the resources available for the sustainable management of forest genetic resources
  - protocols covering protections for Indigenous knowledge relevant to commercial use of forest genetic resources, for both domestic and overseas application.
- Priorities for capacity-building and research include:
  - ability for Indigenous stakeholders and communities to take part in active forest management and commercial use of forests
  - development of skills in sustainable economic management of natural tropical forests.

12.2 International engagement

International organisations, agreements, treaties, conventions and trade agreements to which Australia is a party, and that are directly or indirectly relevant to the conservation, sustainable use and development of forest genetic resources, include those listed in **Table 12**.

Table 12 Australia's international engagement directly or indirectly relevant to forest genetic resources

Convention on Biological Diversity (CBD)
Convention on the Conservation of Migratory Species of Wild Animals (CMS)
Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)
Food and Agriculture Organization of the United Nations (FAO) and its Commission on Genetic Resources for Food and Agriculture (CGRFA)
International Plant Protection Convention (IPPC)
International Tropical Timber Agreement (ITTA)
International Union for the Protection of New Varieties of Plants (UPOV) established under the International Convention for the Protection of New Varieties of Plants (ICPNVP)
Ramsar Convention on Wetlands
United Nations Commission on Sustainable Development (CSD)
United Nations Framework Convention on Climate Change (UNFCCC)
United Nations Forum on Forests (UNFF)
World Heritage Convention
World Intellectual Property Organization (WIPO) and its Intergovernmental Committee on Intellectual Property and Genetic Resources, Traditional Knowledge and Folklore (IGC)
World Trade Organization (WTO)
WTO Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement)

12.2.1 Convention on Biological Diversity

In 1993, Australia became a Party to the Convention on Biological Diversity (CBD). The CBD has three main objectives:

1. the conservation of biological diversity
2. the sustainable use of its components
3. the fair and equitable sharing of the benefits arising out of the utilisation of genetic resources.

The third of these objectives recognises genetic diversity as a component of biodiversity, and underpins substantial subsequent work on the conservation and use of genetic resources across the biosphere, including forest genetic resources.

Australia has had a national biodiversity strategy and action plan in place since 1996[99]. The current plan is *Australia's Strategy for Nature 2019-2030*[100]. All Australian governments have also accepted that access to biological resources in Australia should meet responsibilities under Article 15 of the Convention on Biological Diversity.

Australia has also signed, but not yet ratified, a subordinate instrument to the CBD, the Nagoya Protocol on Access and Benefit Sharing[101]. This protocol establishes a legally binding framework for biotechnology researchers and other scientists to gain access to genetic resources. It also

[99] awe.gov.au/environment/biodiversity/conservation/strategy
[100] australiasnaturehub.gov.au/national-strategy
[101] The Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity; awe.gov.au/science-research/australias-biological-resources/nagoya-protocol-convention-biological

establishes a framework for researchers and developers to share any benefits from genetic resources, or traditional knowledge associated with those resources, with the provider country.

12.3 International collaboration

Australia participates in a number of bilateral, multilateral, sub-regional and regional networks that are directly or indirectly related to forest genetic resources. **Table 13** lists some of the network activities in which Australia has participated since 2013.

Table 13 Overview of the main international activities related to forest genetic resources and carried out through networks

Network name	Activities
Asia Forest Partnership (AFP)	Fosters regional cooperation in research, dissemination of knowledge, and technology transfer
Asia-Pacific Forestry Commission (APFC)	A forum for discussing regional forestry issues, including future directions for the forestry activities by FAO in the region, and for progressing practical work aimed at promoting the adoption of sustainable forest management practices
Asia-Pacific Network for Sustainable Forest Management and Rehabilitation (APFNet)	Capacity-building, information sharing, regional policy dialogues and pilot projects
Australian Centre for International Agricultural Research (ACIAR)	A range of bilateral and multilateral forest research activities
Biodiversity International	Research that promotes conservation and use of tree species
Center for International Forestry Research (CIFOR)	Research
International Union of Forest Research Organizations (IUFRO)	Research
Millennium Seed Bank	*Ex situ* conservation
South Pacific Regional Initiative on Forest Genetic Resources (SPRIG)	Capacity-building and establishment of genetic conservation strategies
World Agroforestry Centre (formerly International Centre for Research in Agroforestry (ICRAF))	Research

Founded in 1982, the Australian Centre for International Agricultural Research (ACIAR[102]) has funded a range of bilateral and multilateral, regional and international projects where Australian researchers collaborate with researchers from developing countries. The ACIAR Forestry Program currently funds collaborative projects and capacity-building in Indonesia, Papua New Guinea, Pacific Islands, Vietnam, Laos, Nepal and Eastern Africa that address priority development themes, including forest tree germplasm conservation, improvement and distribution, and forest restoration, management and protection.

Australia continues to support international agricultural research centres that deal with forestry issues, such as the World Agroforestry Centre[103] (previously ICRAF) of the Consultative Group on International Agricultural Research, and the Center for International Forestry Research[104].

[102] aciar.gov.au/
[103] worldagroforestry.org/
[104] cifor.org/

Current activities of the International Union of Forest Research Organizations relevant to Australian forest tree breeders and geneticists include working groups on conifer and hardwood breeding, and genetic resources.

The private sector is directly engaged in international collaborations on a commercial basis. Tree Breeding Australia is involved in international collaboration on tree improvement programs with organisations in China, Sweden, France and New Zealand. In addition to plantation species grown in Australia, the Tree Breeding Australia DATAPLAN® and TREEPLAN® software systems[105] are being used to house tree improvement data and undertake species-wide genetic evaluations for tree improvement in *Betula pendula*, *Picea abies*, *Pinus contorta*, *P. pinaster*, *P. sylvestris, Larix* species, and a number of tropical and subtropical eucalypts and hybrids.

12.3.1 Regional and international activities

Australia is not a formal member of a regional or sub-regional forest genetic resources conservation network, but participates in a range of regional activities outside Australia.

CSIRO and ACIAR, in association with government, university and private Australian research providers, and the partners and associates of the Australian Seed Bank Partnership (ASBP[106]), are the main national organisations that participate in international collaborations on forest genetic resources. Through these organisations, Australia is involved in international research and development on seed exchange, commercial species tree breeding, and foreign aid projects that assist with forest resource restoration, management and protection. For example, ASBP participates in the global Millenium Seed Bank Partnership[107]. A range of subnational organisations also participate in international research and collaboration on forest genetic resources.

Australia is the coordinator of the Australasian Regional Hub of the DivSeek International Network[108], a not-for-profit organisation that aims to facilitate the generation, integration, and sharing of data and information related to plant genetic resources. The DivSeek charter includes all plant species, with an emphasis on agricultural crops and biodiversity, but the collaboration and networks facilitated by this network will also benefit research and breeding of forest tree and woody plant species.

The Forestry Program of ACIAR funds collaborative projects in a range of countries in the region, aimed at sustainable use of forest genetic resources. ACIAR has collaborative research in Laos and Fiji related to processing small-dimension timber for engineered wood products, with Australian industry an active partner in developing and using this knowledge. ACIAR has also recently initiated development of a forest biosecurity network in south-east Asia, to share data and surveillance techniques for high-risk sites, and build the basis for coordinated biosecurity responses.

Other activities in Australia's region include those listed below:

- The ASBP is part of an informal Asia-Pacific network of species conservation through seed-banking. In 2021 the ASBP presented the Australasian Seed Science Conference.

[105] stba.com.au/technology/dataplan; stba.com.au/technology/treeplan
[106] seedpartnership.org.au/
[107] kew.org/science/collections-and-resources/research-facilities/millennium-seed-bank
[108] divseekintl.org/

- The Cooperative Research Centre for Plant Biosecurity, and its successor the Australian Plant Biosecurity Science Foundation[109], have worked regionally on training and scientific exchange in relation to myrtle rust, which is a global threat to species in the family Myrtaceae, and developed a myrtle rust action plan (see Makinson et al. 2020).
- Australia is a voting participant (from Oceania) in the Global Biodiversity Information Facility.
- Australia is represented on the Intergovernmental Technical Working Group on Forest Genetic Resources through the Southwest Pacific Members of this group (currently Papua New Guinea and Vanuatu, with Fiji and Solomon Islands as alternates).
- HQPlantations are involved in a number of research projects on forest genetic resources, and are a part of an international consortium working on tropical pine genotyping.

12.4 Benefits and results from international and regional cooperation

The benefits to Australia of international cooperation through ACIAR projects have been:

- building improved capacity in Australian research institutions
- improved knowledge of the performance of various Australian trees under different environmental conditions, including many commercially important eucalypts and acacias
- reliable techniques for growing sandalwood plantations
- enhanced networks which facilitate ongoing exchange of scientific information
- the opportunity to monitor the spread of biosecurity threats to forests and forestry, particularly in neighbouring countries in the Pacific region.

12.5 Needs, challenges and opportunities

Needs, challenges and opportunities for international and regional cooperation on forest genetic resources include:

- government, donor and private sector partnerships to expand the resources available for the sustainable management of forest genetic resources
- regional surveillance and information sharing on biosecurity, to protect ecosystems, species health, and genetic diversity, and minimise the spread of pests and diseases
- development of relevant international standards or instruments in international fora
- protocols or best practice approaches covering Indigenous knowledge relevant to commercial use across borders of forest genetic resources and forest products.

12.6 Priorities for capacity-building and research

Priorities for capacity-building and research include:

- ongoing regional biosecurity surveillance and information-sharing
- development of skills in sustainable economic management of natural tropical forests.

[109] apbsf.org.au/myrtle-rust

13 Actions for the future

13.1 Challenges and opportunities for forest genetic resources

13.1.1 Availability of information on forest genetic resources

Australia has accumulated significant information on the genetic resources of its plantation species and selected native forest species. Many eucalypt and acacia species and individual provenances have been characterised using traditional non-molecular methods, and there is a progressive increase in the number of species for which there has been some molecular characterisation.

Most information on forest genetic resources relates to species used in commercial forestry plantations for which there are active tree breeding programs. There is some information on the conservation genetics of individual rare or threatened species. There is limited genetic information for native species grown commercially as small-scale plantations for food, flavourings or other uses, as the underpinning industries are relatively recent and small in scale.

A range of molecular techniques increasingly inform genetic improvement of the main species used for plantation production of timber, fibre, and essential oils, with links to well-established databases and analytical methods. Information from older species and provenance evaluation trials is not always retained in forms that remain available over time (see Booth 2018), but is important to allow integration of older data with more recent data for more powerful modelling, including for trialling new sites and for management under climate change. It will also be important to improve the availability and accessibility of information on accessions currently housed in gene banks (DivSeek 2021).

Coordination of ex situ conservation through seed banks and cryopreservation, such as through the Australian Seed Bank Partnership and the Millennium Seed Bank Partnership, will also be important.

Surrogate measures and indicators for population genetics, health and viability are at times used in identification, listing and conservation management of threatened species. However, lack of information on breeding systems, fecundity and population genetic characteristics limits the scope to tailor management to specific genotypes and locations, as required to ensure the genetic diversity of populations and species is conserved.

Opportunities exist to:

- improve information on the genetic diversity of key forest species, including species with emerging or potential use, in ways that can inform conservation and sustainable use of forest genetic resources at landscape, species and population scales
- improve accessibility of information on forest genetic resources to land managers, conservation managers, established and developing industries, and researchers
- improve understanding of the adaptability of forest genetic resources to climate change, and continue to identify climate change refugia for inclusion in forest reserves and management actions
- improve community understanding of the importance of forest genetic resources for conservation, climate change adaptation, sustainable use and commercial development.

13.1.2 Conservation of forest genetic resources

All native species on the FAO list of forest genetic resources for Australia have at least a proportion of their genetic base conserved in situ. Conservation in situ within protected or managed forests will continue to be the main mechanism for conservation of forest genetic resources in Australia. A proportion of plantation species and a few threatened species also have a proportion of their genetic base conserved ex situ, such as in seed banks, provenance or clonal plantings, seed orchards, seed production areas, and conservation plantings.

A combination of in situ and ex situ conservation and management will be important for both commercial species and threatened species. Ongoing tree breeding and improvement programs will hold genetic resources for commercially important species, but the continuing availability in the wild of the full genetic diversity of a species can provide important natural variation for use in selection for adaptations suitable for future climates, or for resilience against novel pests and diseases. Development of ex situ conservation measures for threatened species can provide insurance against loss of genetic diversity in the wild, and may be more important where the natural adaptive capacity of a species is low, such as in narrow-range endemics (Booth et al. 2015). The concept of climate-adjusted provenancing (Prober et al. 2015) has applications both for commercial species and for environmental plantings.

Opportunities exist to:

- adapt Australia's National Reserve System so that it maintains suitability under predicted climate change (Williams et al. 2016), including by improving vegetation corridors between protected areas to facilitate species movement, and identifying refugia for ongoing protection
- continue action to manage and conserve species severely affected by myrtle rust, in Australia and the Pacific, before their growth and reproductive capacity are seriously diminished in their natural range (Sommerville et al. 2020). This will require provenance collections with a wide range of genotypes, which offer the greatest potential for future selection for disease resistance and production of plants for replanting programs
- continue to manage the impact of both tree plantations and conservation plantings on the genetic integrity of adjacent stands of native forest species
- improve the security of ex situ genetic collections against damage or loss from land-use change, or fire or other natural disasters
- continue to develop ex situ conservation methodologies, including via seed production areas, and to develop strategies to maintain species for which seed is challenging to store by traditional means.

13.1.3 Use, development and management of forest genetic resources

There are opportunities for commercial forestry to:

- continue development of novel technologies for rapid and early trait analysis
- continue to use DNA marker-based genetic and genomic techniques to assist selection and breeding, and decrease the number of breeding cycles and progeny trials needed for establishing breeding values
- continue work on selection for ongoing productivity in future climates and against future risks, including (for species in the Myrtaceae) selections with reduced susceptibility to myrtle rust
- improve private landholder capacity to manage sustainable harvest of native forests and conservation of forest genetic resources on private land

- maintain ongoing access to seed stores and to ex situ conservation locations for all key plantation species
- develop approaches to forest seed collection and supply, and to harvest of non-wood forest products, that allow monitoring of ongoing harvests and comparison to sustainable yields.

There are also opportunities for tea tree and macadamia genetic resources:

- for macadamia, to increase progeny field trial population sizes, improve methods for selection of multiple traits including harvesting efficiency and tree management, increase breeding efficiency using genomic methods, and incorporate wild genetic material as appropriate
- for tea tree, to continue work on genotype effects on oil chemical characteristics, and develop commercially viable clonal propagation methods.

There are also opportunities for Indigenous communities to develop on-country businesses for wild harvest of traditional foods and medicinal plants from forests. This will require:

- development of models for benefit-sharing agreements and protection of traditional knowledge that allow development of commercial enterprises with Indigenous communities.

13.1.4 Policies, institutions and capacity-building

Opportunities exist to:

- continue international and regional cooperation and capacity-building on forest genetic resources, including in the context of biosecurity
- improve coordination of research and programs on forest genetic resources, particularly given Australia's substantial biodiversity, large distances and land areas
- maintain and improve collaboration among institutions, noting that Australia does not have a central coordinating body for forest genetic resources
- continue to implement Australia's myrtle rust, threatened species and biosecurity plans
- review legislation and regulatory arrangements for their suitability for recognising and protecting Indigenous knowledge, and for developing appropriate benefit-sharing agreements
- continue education and extension on the importance of forest genetic resources and its consideration in developing plantings both for commercial and for conservation purposes.

Appendix A Questionnaire responses for the FAO list of forest genetic resources for Australia

This appendix presents questions 11-26 of the FAO Forest Genetic Resources questionnaire 2020 used to collect quantitative data from individual countries for *The Second Report on the State of the World's Forest Genetic Resources* (**Table 14**), and the data table submitted by Australia in response through the FAO OpenForis system for species on the FAO list of forest genetic resources for Australia (**Table 15**).

Table 14 FAO questionnaire for collecting country-level data for *The Second Report on the State of the World's Forest Genetic Resources*

#	Column title	Full question	Form of answer
Q11	Dist	Species for which an up-to-date national distribution range is available	Yes, No, no data
Q12	Non-molec	Species which have been characterized based on non-molecular information	Yes, No, no data
Q13	Molec	Species which have been characterized based on molecular information	Yes, No, no data
Q14	In situ	Species which have been included in in situ conservation programme(s) in your country	Yes, No, no data
Q15	#in situ	Number of in situ conservation units for each of the species in your country	Numerical response, no data
Q16	Area in situ	Area (in hectares) of in situ conservation units for each of the species in your country	Numerical response, no data
Q17	Ex situ	Species which have been included in ex situ conservation programme(s) in your country	Yes, No, no data
Q18	#ex situ	Number of ex situ conservation units for each of the species in your country	Numerical response, no data
Q19	Area ex situ	Area (in hectares) of ex situ conservation units for each of the species in your country	Numerical response, no data
Q20	#ex situ accn	Number of ex situ accessions for each of the species in your country	Numerical response, no data
Q21	Tree seed	Species which have been included in a national (or sub-national) tree seed programme(s) in your country	Yes, No, no data
Q22	Tree breed	Species which have been included in a tree breeding programme in your country	Yes, No, no data
Q23a	Seed stand area	Species for which seed stands are being managed for the production of reproductive material in your country: total area by species	Numerical response, no data
Q23b	#seed stand	Species for which seed stands are being managed for the production of reproductive material in your country: number of seed stands by species	Numerical response, no data
Q24a	Area seed orch	Area of seed orchards by species in your country	Numerical response, no data

Q24b	#seed orch	Number of seed orchards by species in your country	Numerical response, no data
Q25	Macro micro prop	Species for which reproductive material is produced through macro and/or micropropagation, including the amount (average number per year) of planting stock produced by species to the table	Yes, No, no data
Q26	#gen	State of a tree breeding programme by indicating the generation number for species included in the breeding programmes	Numerical response, no data, not applicable

Table 15 Australia's response for species on the FAO list of forest genetic resources for Australia

Responses are constrained to those possible within the OpenForis system: Y, yes; N, No; 0, zero; -, no data (information not available or not provided); n.a., not applicable. The response for Question 17 excludes (is in addition to) the ex situ seed programs covered in Question 21.

	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23a	Q23b	Q24a	Q24b	Q25	Q26
Species	**Dist**	**Non-molec**	**Molec**	**In situ**	**#in situ**	**Area in situ**	**Ex situ**	**#ex situ**	**Area ex situ**	**#ex situ accn**	**Tree seed**	**Tree breed**	**Seed stand area**	**#seed stand**	**Area seed orch**	**#seed orch**	**Macro micro prop**	**#gen**
Acacia auriculiformis	Y	Y	Y	-	-	-	Y	-	-	-	Y	N	0	0	-	-	-	n.a.
A. cincinnata	Y	-	-	-	-	-		-	-	-	Y	-	0	0	-	-	-	-
A. cochlocarpa	Y	-	-	Y	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
A. colei	Y	-	-	-	-	-		-	-	-	Y	-	0	0	-	-	-	-
A. crassicarpa	Y	-	Y	-	-	-	-	-	-	-	Y	N	0	0	-	-	-	n.a.
A. dealbata	Y	Y	Y	-	-	-		-	-	-	Y	N	0	0	-	-	-	n.a.
A. harpophylla	Y	-	-	Y	-	-		-	-	-	Y	-	0	0	-	-	-	-
A. holosericea	Y	-	-	-	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
A. mangium	Y	Y	Y	Y	-	-		-	-	-	Y	N	0	0	-	-	-	-
A. mangium x *A. polystachya* natural hybrid	N	-	-	Y	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
A. mearnsii	Y	Y	Y	-	-	-		-	-	-	Y	-	0	0	-	-	-	-
A. melanoxylon	Y	Y	Y	Y	-	-	Y	-	-	-	Y	Y	0	0	-	-	-	-
A. saligna	Y	Y	Y	-	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
A. simsii	Y	-	-	-	-	-	-	-	-	-	Y	N	0	0	-	-	-	n.a.
Acronychia acidula *	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Agathis robusta	Y	-	Y	-	-	-	-	-	-		Y	-	0	0	-	-	-	-

Species	Q11 Dist	Q12 Non-molec	Q13 Molec	Q14 In situ	Q15 #in situ	Q16 Area in situ	Q17 Ex situ	Q18 #ex situ	Q19 Area ex situ	Q20 #ex situ accn	Q21 Tree seed	Q22 Tree breed	Q23a Seed stand area	Q23b #seed stand	Q24a Area seed orch	Q24b #seed orch	Q25 Macro micro prop	Q26 #gen
Araucaria bidwillii	Y	-	Y	-	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
A. cunninghamii	Y	Y	Y	Y	-	-	Y	-	-	-	Y	Y	0	0	25	9	-	3
Atherosperma moschatum	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Athrotaxis selaginoides	Y	-	-	Y	-	-	-		-	-	Y	-	0	0	-	-	-	-
Atriplex nummularia	Y	Y	-	-	-	-	Y	-	-	-	Y	Y	0	0	-	-	-	-
Backhousia citriodora	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Brachychiton populneus	Y	-	-	-	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
Callitris glaucophylla	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
C. oblonga	Y	-	-	Y	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
Castanospermum australe	Y	-	Y	-	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
Casuarina cunninghamiana	Y	-	Y	Y	-	-	-	-	-	-	Y	N	0	0	-	-	-	n.a.
C. equisetifolia	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
C. obesa	Y	-	-	-	-	-	Y	-	-	-	Y	-	0	0	0.38	1		1
Citrus australasica *	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Corymbia citriodora	Y	Y	Y	Y	-	-	-	-	-	-	Y	Y	0	0	29.3	11	-	1.5
C. henryi	Y	Y	Y	Y	-	-	-	-	-	-	Y	Y	0	0	3	3	-	1
C. maculata	Y	Y	Y	Y	-	-	Y	-	-	-	Y	Y	0	0	15.06	9	-	2
C. torelliana	Y	-	Y	-	-	-	-	-	-	-	Y	Y	0	0	3	2	-	-
Davidsonia jerseyana *	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	
D. pruriens *	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Duboisia myoporoides	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Elaeocarpus angustifolius (grandis)	Y	-	Y	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
E. reticulatus	Y		Y	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Eucalyptus argophloia	Y	Y			-	-	Y	-	-	-	Y	Y	0	0	5.5	4	-	1
E. astringens	Y	-	-	-	-	-		-	-	-	Y	Y	0	0	-	-	-	-
E. barberi	Y	-	-	-	-	-	Y	-	-	-	Y	N	0	0	-	-	-	n.a.

	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23a	Q23b	Q24a	Q24b	Q25	Q26
Species	**Dist**	**Non-molec**	**Molec**	**In situ**	**#in situ**	**Area in situ**	**Ex situ**	**#ex situ**	**Area ex situ**	**#ex situ accn**	**Tree seed**	**Tree breed**	**Seed stand area**	**#seed stand**	**Area seed orch**	**#seed orch**	**Macro micro prop**	**#gen**
E. benthamii	Y	-	-	-	-	-	Y	-	-	-	Y	Y	0	0	10	5	-	2
E. botryoides	Y	-	-	Y	-	-	-	-	-	-	Y	Y	0	0	0.76	2	-	1
E. burdettiana	Y	-	-	Y	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
E. camaldulensis	Y	Y	Y	Y	-	-	Y	-	-	-	Y	Y	0	0	>1.81	3	-	1
E. cladocalyx	Y	Y	Y	-	-	-	-	-	-	-	Y	Y	Y	-	19.38	15	-	1
E. cloeziana	Y	-	Y	-	-	-	-	-	-	-	Y	Y	0	0	7	2	-	1
E. conglomerata	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
E. crebra	Y	-	-	-	-	-	-	-	-	-	Y	Y	0	0	-	-	-	-
E. crenulata	Y	-	-	Y	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
E. deglupta	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
E. delegatensis	Y	Y	-	-	-	-	-	-	-	-	Y	N	0	0	-	-	-	n.a.
E. diversicolor	Y	-	-	Y	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
E. dunnii	Y	Y	-	-	-	-	-	-	-	-	Y	Y	0	0	27.04	13	-	2
E. fastigata	Y	Y	-	Y	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
E. globulus	Y	Y	Y	Y	-	-	Y	-	-	-	Y	Y	0	0	53.85	20	-	4
E. grandis	Y	Y	Y	Y	-	-	-	-	-	-	Y	Y	0	0	9.04	5	-	1.5
E. gunnii	Y	-	-	-	-	-	-	-	-	-	Y	N	0	0	-	-	-	n.a.
E. horistes	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
E. kartzoffiana	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
E. kochii	Y	-	-	-	-	-	-		-	-	Y	N	0	0	9	8	-	1
E. laevopinea	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
E. leucoxylon	Y	-	-	-	-	-	-	-	-	-	Y	Y	0	0	-	-	-	-
E. longirostrata	Y	-	-	-	-	-	-	-	-	-	Y	Y	0	0	Y	-	-	-
E. loxophleba	Y	Y	Y	-	-	-	Y		-	-	Y	N	0	0	22.25	12	-	1
E. marginata	Y	Y	-	Y	-	-	Y	-	-	-	Y	-	0	0	3.17	2	-	1
E. melliodora	Y	-	Y	-	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
E. moluccana	Y	-	-	-	-	-	Y	-	-	-	Y	N	0	0	-	-	-	n.a.

	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23a	Q23b	Q24a	Q24b	Q25	Q26
Species	**Dist**	**Non-molec**	**Molec**	**In situ**	**#in situ**	**Area in situ**	**Ex situ**	**#ex situ**	**Area ex situ**	**#ex situ accn**	**Tree seed**	**Tree breed**	**Seed stand area**	**#seed stand**	**Area seed orch**	**#seed orch**	**Macro micro prop**	**#gen**
E. morrisbyi	Y	Y	Y	Y	-	-	Y	-	-	-	Y	N	0	0	-	-	-	n.a.
E. nitens	Y	Y	Y	Y	-	-	-	-	-	-	Y	Y	0	0	28.05	14	-	3
E. obliqua	Y	Y	-	Y	-	-	-		-	-	Y	N	0	0	-	-	-	n.a.
E. occidentalis	Y	Y	-	-	-	-	-	-	-	-	Y	Y	0	0	5.58	10	-	1
E. ovata	Y	-	-	Y	-	-	Y	-	-	-	Y	N	0	0	-	-	-	n.a.
E. pellita	Y	Y	Y	-	-	-	-	-	-	-	Y	N	0	0	-	-	-	n.a.
E. pilularis	Y	Y	Y	Y	-	-	-	-	-	-	Y	Y	0	0	15	5	-	1
E. polybractea	Y	-	-	-	-	-	Y	-	-	-	Y	Y	0	0	>17.4	18	-	1
E. punctata (previously *E. biturbinata*)	Y	-	-	-	-	-	-	-	-	-	Y	Y	0	0	0.5	1	-	-
E. radiata	Y	-	-	-	-	-	-	-	-	-	Y	N	0	0	-	-	-	n.a.
E. raveretiana	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
E. regnans	Y	Y	Y	Y	-	-	-	-	-	-	Y	N	0	0	-	-	-	n.a.
E. remota	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	n.a.
E. rudis	Y	-	-	-	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
E. saligna	Y	Y	-	Y	-	-	-	-	-	-	Y	Y	0	0	12.85	7	-	1
E. saligna x *E. botryoides* natural hybrid	N	-	-	Y	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
E. scoparia	Y	-	-	-	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
E. sideroxylon	Y	-	-	Y	-	-	-	-	-	-	Y	Y	0	0	2.44	3	-	1
E. sieberi	Y	Y	Y	-	-	-	-	-	-	-	Y	N	0	0	-	-	-	n.a.
E. smithii	Y	-	-	-	-	-	-	-	-	-	Y	Y	0	0	7	3	-	1
E. tereticornis	Y	-	-	Y	-	-	-	-	-	-	Y	Y	0	0	-	-	-	-
E. tricarpa	Y	Y	Y	-	-	-	Y	-	-	-	Y	Y	0	0	4.13	5	-	1
E. urophylla	Y	Y	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
E. viminalis	Y	-	-	Y	-	-	Y	-	-	-	Y	N	0	0	0.32	1	-	-
Eucryphia lucida	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-

Species	Q11 Dist	Q12 Non-molec	Q13 Molec	Q14 In situ	Q15 #in situ	Q16 Area in situ	Q17 Ex situ	Q18 #ex situ	Q19 Area ex situ	Q20 #ex situ accn	Q21 Tree seed	Q22 Tree breed	Q23a Seed stand area	Q23b #seed stand	Q24a Area seed orch	Q24b #seed orch	Q25 Macro micro prop	Q26 #gen
Ficus macrophylla	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Flindersia australis	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
F. brayleyana	Y	-	Y	Y	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Fontainea picrosperma	Y	-	Y	-	-	-	-	-	-	-	N	-	0	0	-	-	-	-
Grevillea robusta	Y	Y	Y	Y	-	-	Y	-	-	-	Y	Y	0	0	1.25	2	-	1
Khaya senegalensis	Y	-	-	-	-	-	Y	-	-	-	Y	Y	0	0	3	1	-	-
Lagarostrobos franklinii	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	n.a.
Macadamia integrifolia	Y	Y	Y	Y	-	-	Y	-	-	-	Y	Y	0	0	-	-	-	2
M. tetraphylla	Y	Y	Y	Y	-	-	Y	-	-	-	Y	Y	0	0	-	-	-	-
Melaleuca alternifolia	Y	-	Y	-	-	-	Y	-	-	-	Y	Y	0	0	Y	-	-	3
M. uncinata	Y	-	-	-	-	-	Y	-	-	-	Y	Y	0	0	-	-	-	-
Melia azedarach	Y	-	-	-	-	-	Y	-	-	-	Y	N	0	0	-	-	-	n.a.
Nothofagus cunninghamii	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Picea abies	Y	-	-	-	-	-	Y	-	-	-	Y	-	0	0	-	-	-	
Pinus brutia	Y	Y	-	-	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
P. caribaea	Y	Y	Y	-	-	-	Y	-	-	-	Y	Y	0	0	19	6	-	-
P. elliottii	Y	Y	Y	-	-	-	Y	-	-	-	Y	Y	0	0	6	1	-	-
PEE x PCH hybrid (*P. elliottii x P. caribaea* hybrid)	n.a.	-	-	-	-	-	Y	-	-	-	Y	Y			27	9		-
P. halepensis	Y	-	-	-	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
P. pinaster	Y	Y	Y	-	-	-	-	-	-	-	Y	N	0	0	-	-	-	-
P. radiata	Y	Y	Y	-	-	-	Y	-	-	-	Y	Y	0	0	-	-	-	4
Podocarpus elatus	Y	-	Y	-	-	-	-	-	-	-	Y	N	0	0	-	-	-	n.a.
Pterocarpus macrocarpus	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Santalum acuminatum	Y	-	-	-	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-
S. album	Y	-	-	-	-	-	-	-	-	-	Y	Y	0	0	21.2	5	-	1
S. lanceolatum	Y	-	-	-	-	-	Y	-	-	-	Y	Y	0	0	0.5	2	-	1

	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23a	Q23b	Q24a	Q24b	Q25	Q26
Species	**Dist**	**Non-molec**	**Molec**	**In situ**	**#in situ**	**Area in situ**	**Ex situ**	**#ex situ**	**Area ex situ**	**#ex situ accn**	**Tree seed**	**Tree breed**	**Seed stand area**	**#seed stand**	**Area seed orch**	**#seed orch**	**Macro micro prop**	**#gen**
S. spicatum	Y	Y	-	-	-	-	Y	-	-	-	Y	Y	0	0	8.77	5	-	1
Swietenia macrophylla	N	-	-	-	-	-	-	-	-	-	Y	N	0	0	-	-	-	n.a.
Syzygium anisatum *	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
S. luehmannii *	Y	-	-	-	-	-	-	-	-	-	N	-	0	0	-	-	-	-
Tasmannia lanceolata *	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Tectona grandis	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Terminalia ferdinandiana	Y	-	-	-	-	-	-	-	-	-	Y	-	0	0	-	-	-	-
Toona ciliata	Y	-	-	Y	-	-	-	-	-	-	Y	N	0	0	-	-	-	n.a.
Wollemia nobilis	Y	Y	Y	Y	-	-	Y	-	-	-	Y	-	0	0	-	-	-	-

* forest species registered with Food Standards Australia New Zealand (FSANZ) and developed in the Australian and international markets.

Y, yes; N, No; 0, zero; -, no data (information not available or not provided); n.a., not applicable.

Appendix B Attributes and uses of species on the FAO list of forest genetic resources for Australia

Table 16 Column headings and attribute abbreviations used in species attributes table

Abbreviation	Column title	Attribute
Tree/Other	Tree or Other (shrub)	T, tree; O, other; T/O, mainly tree, sometimes shrub depending on location; O/T, mainly shrub, sometimes tree; M, mallee
Nat/exotic	Native or exotic	N, native; E, exotic; N/E, native with subspecies outside Australia
Endem	Endemic	Y, Yes; N, No; n.a., not applicable (exotic species)
Distn	Widespread, regional or localised distribution	WW, very widespread; W, widespread (species occurs across wide range of latitudes and/or longitudes within Australia); R, regional (within one Australian state, across the border of two states, or restricted to a vegetation type); L, local; LL, very localised; n.a., not applicable
Range disjunc	Range disjunction	Y, Yes; -, not obviously; n.a., not applicable. Not scored as Y where species distribution is interrupted by small areas of a different vegetation type, or by Bass Strait
Plantn Aust	Plantation species in Australia	Y, Yes; (Y), minor; -, not applicable
NF	Native forest harvest in Australia	Y, Yes; (Y), minor or previous; -, not applicable
Wood	Wood or fibre use	S, solid wood; P, pulpwood; SP, both solid wood and pulpwood; H; high-value or specialty timber
Food	Food use	Y, Yes; -, No
Other	Other uses (within or outside Australia)	Agr, agroforestry/crop support; C, carbon offset plantings; Cha, charcoal; Dye, used for dyeing; E, energy/biomass; H, honey; (H), minor use for honey; Host, host for sandalwood plantations; Fences, used for brushwood fences; Fo, fodder; Fu, fuelwood; M, medicinal; Oil, essential oil; Per, perfume; Res, resin; Ta, tannin
Envtl or social	Environmental service or social value (within or outside Australia)	Cult, cultivated as street tree or ornamental tree; S, shelter or windbreak; So, soil conservation/ land rehabilitation; D, dune stabilisation; Sa, saline site rehabilitation
Imp O/S	Important overseas	Y, Yes; (Y), minor; -, No or not significantly
Iconic sp	Iconic species in Australia: well-known; distinctive; particularly tall; ancient species	Y, Yes; -, Not significantly
Indig imp	Importance to Indigenous (Aboriginal or Torres Strait Islander) peoples	Y, Yes; -, data unavailable. May underrepresent traditional Indigenous use of Australian native species.

? indicates uncertainly around an attribute designation

Table 17 Attributes and uses of species on the FAO list of forest genetic resources for Australia

Species	Tree/ Other	Nat/ exotic	Endem	Distn	Range disjunc	Plantn Aust	NF	Wood	Food	Other	Envtl or social	Imp O/S	Iconic sp	Indig imp
Acacia auriculiformis	T/O	N	N	R	Y	Y	-	SP	-	Fu, Fo, Agr, H	S, So, Cult	Y	-	Y
A. cincinnata	T/O	N	Y	R	Y	-	-	S	-	Agr, So	-	Y	-	-
A. cochlocarpa	O	N	Y	L	Y	-	-	-	-	-	-	-	-	-
A. colei	O	N	Y	W	-	-	-	S	Y	Fu, Cha	S, So	Y	-	-
A. crassicarpa	T	N	N	R	Y	-	-	S	-	Fu, Cha	S, So, D	Y	-	Y
A. dealbata	O/T	N	Y	R	-	-	-	SP	Y	Fo, H, Per	S, So, Cult	(Y)	-	-
A. harpophylla	T	N	Y	R	Y?	-	-	S	-	Fu, Fe	S	-	Y	Y
A. holosericea	O/T	N	N	W	Y?	-	-	S	-	Cha	-	Y	-	-
A. mangium	T	N	N	R	Y	Y	-	SP	-	Fo, Fu, Cha, H	So	Y	-	-
A. mangium x *A. polystachya* natural hybrid	-	N	-	-	-	-	-	-	-	-	-	-	-	-
A. mearnsii	O/T	N	Y	R	-	-	-	SP	-	Fu, Cha, Ta, Agr	S, So	Y	-	Y
A. melanoxylon	T/O	N	Y	W	Y	Y	-	S, H	Y	Fo, Fu,M, Dye	S, Cult	Y	-	Y
A. saligna	O/T	N	Y	R	-	-	-	-	-	Fu, Fo	S, Sa, So, C	Y	-	-
A. simsii	O	N	N	W	Y	-	-	-	-	Host	-	-	-	-
Acronychia acidula *	T	N	Y	R	Y	(Y)			Y					Y
Agathis robusta	T	N	N/E	R	YY	-	-	S	-	-	-	-	Y	-
Araucaria bidwillii	T	N	Y	L	YY	-	-	S, H	Y	-	Cult	-	Y	Y
A. cunninghamii	T	N	N	R	Y	Y	-	S, H	-	-	Cult	-	Y	-
Atherosperma moschatum	T/O	N	Y	R	Y	-	(Y)	S, H	Y	M	Cult	-	-	-
Athrotaxis selaginoides	T	N	Y	R	N	-	(Y)	S, H	-	-	-	-	Y	-
Atriplex nummularia	O	N	Y	W	Y	(Y)		-	Y	Fo	So	-	Y	Y
Backhousia citriodora	O/T	N	Y	R	Y	(Y)	-	(H)	Y	M	Cult	(Y)	-	Y
Brachychiton populneus	T	N	Y	W	-	-	-	-	Y	Fo	-	-	Y	Y
Callitris glaucophylla	T	N	Y	W	Y	-	(Y)	S, H	-	M, Oil	Cult	-	Y	Y
C. oblonga	O/T	N	Y	R	Y	-	-	-	-	-	S	-	-	-
Castanospermum australe	T	N	N	R	Y	(Y)	(Y)	S, H	Y	-	S, Cult	-	-	Y

Species	Tree/ Other	Nat/ exotic	Endem	Distn	Range disjunc	Plantn Aust	NF	Wood	Food	Other	Envtl or social	Imp O/S	Iconic sp	Indig imp
Casuarina cunninghamiana	T	N	Y	W	-	(Y)	-	S	-	Fu	S, D, Cult	Y	Y	-
C. equisetifolia	T	N	N	W	-	-	-	S	-	Fu	S, D	Y	-	-
C. obesa	T	N	Y	W	Y	Y	-	S	-	-	Sa, Cult	-	-	-
Citrus australasica *	O/T	N	Y	R	Y	(Y)	-	(H)	Y	-	-	-	-	Y
Corymbia citriodora	T	N	y	R	YY	Y		S	-	H, Oil, M, Fu	Cult	Y	Y	Y
C. henryi	T	N	Y	R	Y	Y	-	S	-	-	-	-	-	-
C. maculata	T	N	Y	W	YY	Y	Y	S	-	-	Cult	Y	Y	-
C. torelliana	T	N	Y	L	-	Y	-	S	-	-	Cult	-	-	-
Davidsonia jerseyana *	T	N	Y	L	-	(Y)	-	-	Y	-	Cult	-	-	Y
D. pruriens *	T	N	Y	R	-	(Y)	(Y)	-	Y	-	Cult	-	-	Y
Duboisia myoporoides	O/T	N	N	R	YY	(Y)	-	-	-	M	-	-	-	-
Elaeocarpus angustifolius	T	N	N	R	Y	(Y)	(Y)	S, H	-	-	-	-	Y	-
E. reticulatus	T/O	N	Y	W	-	-	-	-	Y	-	Cult	-	-	Y
Eucalyptus argophloia	T	N	Y	LL	-	(Y)	-	S	-	-	-	-	-	-
E. astringens	T	N	Y	R	-	(Y)?	-	S	-	Fu	-	Y	-	-
E. barberi	T/M	N	Y	L	-	-	-	-	-	-	S, Cult	-	-	-
E. benthamii	T	N	Y	L	Y	(Y)	-	P	-	-	-	Y	-	-
E. botryoides	T	N	E	R	Y	(Y)	-	S	-	-	-	Y	-	-
E. burdettiana	O	N	Y	L	-	-	-	-	-	-	-	-	-	-
E. camaldulensis	T	N	E	WW	Y	(Y)	-	SP, H	-	H, Oil, M, Fu	So, Sa	Y	Y	-
E. cladocalyx	T	N	Y	L	YY	Y	-	S	-	Fu	S	Y	-	-
E. cloeziana	T	N	Y	R	YY	(Y)	-	S	-	Fu	-	Y	-	-
E. conglomerata	T/O	N	Y	L	-	-	-	-	-	-	-	-	-	-
E. crebra	T	N	Y	WW	(Y)	(Y)	-	S	-	H	S, Cult	S	-	-
E. crenulata	T	N	Y	LL	Y	-	-	-	-	-	Cult	-	-	-
E. deglupta	T	E	N	n.a.	Y	(Y)	-	SP	-	-	Cult	Y	-	-
E. delegatensis	T	N	Y	R	Y	-	Y	SP, H	-	-	-	Y	Y	-
E. diversicolor	T	N	Y	R	-	-	Y	SP	-	H	-	Y	Y	-
E. dunnii	T	N	Y	L	Y	(Y)	-	SP	-	-	-	Y	-	-

Species	Tree/ Other	Nat/ exotic	Endem	Distn	Range disjunc	Plantn Aust	NF	Wood	Food	Other	Envtl or social	Imp O/S	Iconic sp	Indig imp
E. fastigata	T	N	Y	R	Y	-	Y	SP	-	-	S, Cult	Y	-	-
E. globulus	T	N	Y	R	YY	Y	-	SP	-	-	S	Y	-	-
E. grandis	T	N	Y	R	YY	Y	-	SP	-	-	Cult	Y	Y	-
E. gunnii	T	N	Y	L	(Y)	-	-	-	-	Oil	cult	Y	-	Y
E. horistes	O/T	N	Y	R	-	-	-	-	-	Oil, E	So	-	-	-
E. kartzoffiana	T	N	Y	L	-	-		-	-	-	-	-	-	-
E. kochii	O/T	N	Y	R	Y	Y	-	-	-	Oil	-	-	-	-
E. laevopinea	T	N	Y	R	(Y)	-	Y	S	-	-	-	-	-	-
E. leucoxylon	T	N	Y	R	Y	(Y)	-	S	-	H, Oil	-	-	-	-
E. longirostrata	T	N	Y	R	-	(Y)	-	S	-	-	-	-	-	-
E. loxophleba	T/O	N	Y	W	-	Y	-	S	-	Oil	Sa, C	-	-	-
E. marginata	T	N	Y	R	Y	-	Y	S, H	-	H, Charc	So	-	Y	-
E. melliodora	T	N	Y	WW	Y	-	-	S	-	H, Fu	So	Y	-	-
E. moluccana	T	N	Y	WW	Y	(Y)	-	S	-	Fu	-	-	-	-
E. morrisbyi	T	N	Y	L	-	-	-	-	-	-	Cult	-	-	-
E. nitens	T	N	Y	R	YY	Y	-	SP	-	Oil	-	Y	-	-
E. obliqua	T	N	Y	WW	(Y)	-	Y	SP, H	-	-	-	Y	-	-
E. occidentalis	T/O	N	Y	R	-	(Y)	-	SP	-	Fu	S, So, Sa	Y	-	-
E. ovata	T	N	Y	WW	Y	-	Y	S	-	Agr	-	-	-	-
E. pellita	T	N	Y	R	YY	(Y)	-	S	-	-	-	Y	-	-
E. pilularis	T	N	Y	R	Y	(Y)	Y	S	-	-	-	(Y)	-	-
E. polybractea	O	N	Y	R	Y	Y	-	-	-	Oil	C	-	-	Y
E. punctata (previously *E. biturbinata*)	T	N	Y	R	Y	(Y)	-	S	-	-	-	Y	-	-
E. radiata	T	N	Y	W	-	-	Y?	S	-	Oil	-	-	-	-
E. raveretiana	T	N	Y	R	Y	-	-	-	-	-	-	-	-	-
E. regnans	T	N	Y	R	-	(Y)	Y	SP, H	-	-	-	Y	Y	-
E. remota	T/O	N	Y	L	-	-	-	-	-	S	-	-	-	-
E. rudis	T	N	Y	WW	-	-	-	S	-	H, Fu, E	Sa	-	-	-

Species	Tree/ Other	Nat/ exotic	Endem	Distn	Range disjunc	Plantn Aust	NF	Wood	Food	Other	Envtl or social	Imp O/S	Iconic sp	Indig imp
E. saligna	T	N	Y	W	Y	(Y)	-	SP	-	Fu	-	Y	Y	-
E. saligna x *E. botryoides* natural hybrid	T	N	-	-	-	-	-	-	-	-	-	-	-	-
E. scoparia	T	N	Y	L	Y	-	-	-	-	-	Cult	-	-	-
E. sideroxylon	T	N	Y	WW	-	(Y)	-	S	-	Fu, H, Oil	-	Y	-	-
E. sieberi	T	N	Y	W	-	(Y)	Y	SP	-	-	-	-	-	-
E. smithii	T	N	Y	R	-	Y	-	SP	-	Oil	-	Y	-	-
E. tereticornis	T	N	N	WW	Y	-	-	SP	-	Oil, H, Fu	-	Y	Y	-
E. tricarpa	T	N	Y	R	Y	(Y)	-	S	-	-	-	-	-	-
E. urophylla	T	E	N	n.a.	n.a.	Y	-	SP	-	Charc	-	Y	-	-
E. viminalis	T	N	Y	WW	-	(Y)	-	SP	-	-	-	Y	-	Y
Eucryphia lucida	T/O	N	Y	R	-	-	Y	H	-	H	Cult	-	-	-
Ficus macrophylla	T	N	N	R	Y	-	-	S	-	-	Cult	(Y)	Y	Y
Flindersia australis	T	N	Y	W	Y	(Y)	-	S, H	-	-	-	-	-	-
F. brayleyana	T	N	Y	R	Y	(Y)	-	S, H	-	-	-	-	-	-
Fontainea picrosperma	T	N	Y	L	-	(Y)	(Y)	-	-	M	-	-	-	-
Grevillea robusta	T	N	Y	R	-	(Y)	Y	S, H	-	Fu, H	S, Cult	Y	Y	-
Khaya senegalensis	T	E	N	n.a.	n.a.	Y	-	S	-	Fo, M	Cult	Y	-	-
Lagarostrobos franklinii	T	N	Y	R	-	-	Y	S, H	-	Oil	-	-	Y	-
Macadamia integrifolia	T	N	Y	R	-	Y	-	-	Y	-	-	Y	-	Y
M. tetraphylla	T/O	N	Y	R	-	Y	-	-	Y	-	-	Y	-	Y
Melaleuca alternifolia	T/O	N	Y	R	-	Y	-	-	-	Oil, M	-	-	-	Y
M. uncinata	O	N	Y	W	-	(Y)	Y	-	-	Fences, Oil	-	-	-	Y
Melia azedarach	T	N	N	W	-	-	-	S, H	-	Oil, M	Cult	Y	-	-
Nothofagus cunninghamii	T/O	N	Y	R	Y	-	-	S, H	-	-	-	-	Y	-
Picea abies	T	E	n.a.	n.a.	n.a.	-	-	SP	-	-	S, Cult	Y	-	-
Pinus brutia	T	E	n.a.	n.a.	n.a.	(Y)	-	SP	-	-	-	-	-	-
P. caribaea	T	E	n.a.	n.a.	n.a.	Y	-	S	-	-	-	Y	-	-
P. elliottii	T	E	n.a.	n.a.	n.a.	Y	-	S	-	-	-	Y	-	-

Species	Tree/ Other	Nat/ exotic	Endem	Distn	Range disjunc	Plantn Aust	NF	Wood	Food	Other	Envtl or social	Imp O/S	Iconic sp	Indig imp
PEE x PCH hybrid (*P. elliottii x P. caribaea* hybrid)	T	E	n.a.	n.a.	n.a.	Y	-	S	-	-	-	-	-	-
P. halepensis	T	E	n.a.	n.a.	n.a.	(Y)	-	S	Y	-	Cult	-	-	-
P. pinaster	T	E	n.a.	n.a.	n.a.	Y	-	S	-	Res	-	-	-	-
P. radiata	T	E	n.a.	n.a.	n.a.	Y		SP	-	-	-	Y	--	
Podocarpus elatus	T	N	N	W	Y	-	Y	S, H	Y	-	Cult	-	Y	Y
Pterocarpus macrocarpus	T	E	n.a.	n.a.	n.a.	-	-	S	-	-	S, Cult	Y	-	-
Santalum acuminatum	T/O	N	Y	W	Y	(Y)	Y	-	Y	-	-	-	Y	Y
S. album	O	N	N	R	Y	Y	-	S	-	Oil	-	Y	-	-
S. lanceolatum	O	N	Y	WW	-	-	Y	S	-	Oil	-	-	-	-
S. spicatum	O	N	Y	WW	Y	Y	Y	S	-	Oil	-	-	-	Y
Swietenia macrophylla	T	E	n.a.	n.a.	n.a.	-	-	S, H	-	-	-	-	-	-
Syzygium anisatum *	O	N	Y	L	Y	(Y)	-	-	Y	-	-	-	-	Y?
S. luehmannii *	T	N	Y	W	YY	(Y)	(Y)	-	Y	-	Cult	-	-	Y
Tasmannia lanceolata *	O/T	N	Y	W	Y	-	Y	-	Y	M	-	-	-	Y?
Tectona grandis	T	E	n.a	n.a	n.a	(Y)	n.a.	S, H	-	-	-	Y	-	-
Terminalia ferdinandiana	T	N	Y	W	Y	(Y)	Y	-	Y	M	-	-	-	Y
Toona ciliata	T	N	N	W	YY	(Y)	-	S, H	-	Dye, M	-	Y	Y	-
Wollemia nobilis	T	N	Y	L	-	-	-	-	-	-	-	-	Y	-

* forest species registered with Food Standards Australia New Zealand (FSANZ) and developed in the Australian and international markets.
Main sources: Boland et al. (1992), Turnbull and Pryor (1984), Sultanbawa and Sultanbawa (2016), species profiles in the Atlas of Living Australia (bie.ela.org.au) and Flora of Australia (profiles.ala.org.au/opus/foa); and author RL's expert knowledge.
Supplementary sources: Rossetto et al. (2017); selected species profiles in PlantNet (plantnet.rbgsyd.nsw.gov.au/), Useful Tropical Plants (tropical.theferns.info/), Useful Temperate Plants (temperate.theferns.info/), The Gymnosperm Database (conifers.org/), Australian Rainforest Plants (lucidcentral.org/editors-pick-animal-and-plant-identification-keys/australian-rainforest-plant-keys/), CABI Invasive Species Compendium (cabi.org/isc/), and other websites (sbs.com.au/nitv/nitv-news/article/2018/08/22/cider-trees-researchers-tap-indigenous-fermentation-processes; sttas.com.au/products-customers/nursery-and-seed-centre/eucalypt/barbers-gum; search.informit.org/doi/10.3316/INFORMIT.0958554854; transport.tas.gov.au/__data/assets/pdf_file/0009/275247/EDA_Tree_Assessment_Framework_Final_July_2018.pdf).

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