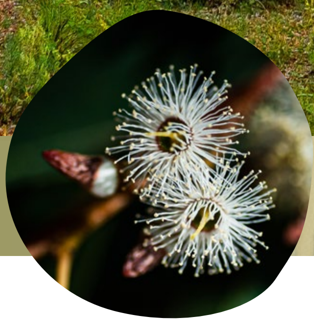
Identifying gaps in knowledge, management and conservation in the Northern Jarrah Forest

A literature review



The Western Australian Biodiversity Science Institute

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Acknowledgement of Country

We acknowledge the traditional custodians throughout Australia and their continuing connection to, and deep knowledge of, the land and waters. We pay our respects to Elders both past and present.

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Contents

Executive summary

The Northern Jarrah Forest (NJF) is a significant environmental asset in Western Australia, but historical and ongoing use, as well as the impacts of climate change, means the management of the forest needs careful consideration. Large areas of the NJF were cleared for agriculture and, timber from the region initially supporting the development of Perth. Consequently, almost all of the forest has been harvested more than once, altering the structure of the jarrah forest in many areas towards smaller, more densely packed trees. Forestry for commercial native timber harvesting in the NJF ceased in 2024, however the NJF is utilised by several other industries. Mining is now the largest industry in the NJF both in terms of area of use and economic benefit, however, agriculture (and other rural land uses) is also significant. Tourism, beekeeping and seed collection are also industries that utilise the NJF.

Regardless, the NJF retains high environmental significance, supporting significant waterways, a diverse floral assemblage and providing significant habitat for many fauna species, including eight threatened ecological communities, 125 listed threatened species and nine migratory species. The NJF is of high cultural significance to Aboriginal people, including more than 600 registered Aboriginal sites. Although the NJF is actively managed and restoration is undertaken, the forest is under increasing pressure from the effects of decreased rainfall and increased temperatures due to climate change; impacts from clearing for mining, forestry (historically) and agriculture; altered fire regimes; and the impacts of disease and invasive species, particularly *Phytophthora cinnamomi* and feral cats and foxes. The protection of land from further clearing, restoration and forest management actions (including ecological thinning, burning regimes and disease and pest management) are all solutions that are currently employed to reduce some of these pressures.

Despite being a region that has been extensively studied, there remains some gaps in knowledge for the NJF, particularly in relation to the changing climate. The pre-European structure and function of the NJF and patterns of natural disturbance for the NJF are not well resolved, nor are the levels of recovery achieved for vegetation composition and fauna recolonisation. Representative indicator species for key ecosystem functions and services are yet to be identified and further knowledge of species inhabiting the NJF is required. Investigation into alternative measures of legal protection of land from clearing would also be advantageous.

Given the significance of the NJF, the resilience and health of the jarrah forest needs to be balanced with the economic and social priorities for the region. Key approaches specific to the NJF include: ecological management for improved water yields, legal protection of priority conservation areas, restoration, disease and invasive species management, addressing knowledge gaps, and adopting collaborative approaches with agriculturalists, Aboriginal people and local communities.

Where social and economic needs cause a negative impact on environmental values, environmental offsets are a tool to ensure this is counterbalanced. The strategic use of offsets can provide opportunities for funding to expand and/or ensure the ongoing longevity of these activities. However, to ensure that offsets are strategic, consideration of the environmental, cultural, social and economic priorities for the NJF must be factored into offset planning and design. The use of mapping and data analysis provides an opportunity to identify areas that could be prioritised for protection, restoration, and management activities including through environmental offsets and other crediting mechanisms. This literature review is the first stage of a research project that seeks to identify strategic regional opportunities, in recognition of sustainable development, for environmental offsets within the NJF.

Document scope

Alcoa, Newmont and South32 are mining proponents operating in the Northern Jarrah Forest subregion (NJF). Mining proponents are required to adhere to government requirements for the minimisation of impacts to the environment resulting from mining activities. Further, as members of the International Council on Mining and Metals (ICMM), Alcoa, Newmont and South32 are also committed to ICMMs Mining Principles that require further performance expectations, including continual improvement in environmental performance, conservation of biodiversity, integrated approaches to land-use planning and contribution to social and economic development (ICMM, 2024). With resource extraction proposed to continue in the NJF, a strategic, regional scale approach to environmental offsets has been proposed to contribute to the minimisation of environmental impacts and these Mining Principles for the benefit of sustainable development.

Consideration of offsets at a regional scale can ensure better consideration of cumulative impacts, key priorities and adaptive management; improve ecological connectivity and the quality of environmental outcomes; and better inform risk mitigations to prevent offset failure (Abdo et al., 2019; EPA, 2024a; Gardner et al., 2013; Kiesecker et al., 2009; Rosa et al., 2022; Samuel, 2020; Takacs, 2018). Similarly, these advantages also have benefits for the promotion of socioeconomic benefits and sustainable development (WEF, 2016).

The strategic approach to offsets in the NJF will not focus on individual environmental attributes across the region. Instead, this strategic approach will provide a regional approach to restoration and the management of key environmental priorities across the NJF with consideration to cultural, social and economic priorities. Strategic approaches to offsets can improve efficiency, minimise costs, optimise outcomes, reduce risks and support alternative solutions such as advanced offsets or conservation funds (Abdo et al., 2019; Bell, 2016; Koh et al.,2014; Lukey et al. 2017; Simpson et al., 2017)

Alcoa, Newmont and South 32 are working with The Western Australian Biodiversity Science Institute to share knowledge, data and resources for a collaborative approach that guide decisions around strategic offsetting. In recognition of this, a working group has been created to undertake a project to develop a strategy for environmental offsets in the northern jarrah forest.

The project will be undertaken in three stages:

Stage 1: review of literature and identification of gaps and opportunities for the contribution to the reduction of key pressures to the NJF.

Stage 2: review and assess relevant spatial data and reports with context to gaps and opportunities identified by the literature review. It is likely that this stage will also identify new gaps and opportunities.

Stage 3: utilising the information collected and assessed in stages 1 and 2, develop a report that provides strategic offset solutions including avoidance areas and areas that could be prioritised for conservation, restoration and management.

The strategic approach to offsets for the NJF region is aligned with Recommended Priority 2 of the Western Australian Environmental Protection Authority's *Public Advice: Considering environmental offsets at a regional scale*, which states: regional plans should be developed that "are logically and strategically located in areas of greatest regional environmental benefit" and "regional conservation and restoration offset opportunities should be developed" (EPA, 2024a).

This project will identify areas for avoidance and conservation, which is consistent with the National Objectives within the Commonwealth Governments draft *National Environmental Standard for Regional Planning* (DCCEEW, 2024a). Additionally, this project will identify conservation priorities that can be used for environmental offsets, which is consistent with the recommendations of the *Independent Review of the EPBC Act – Final Report* (Samuel, 2020).

Offset regulators and other government departments are being consulted and throughout each stage of this project to ensure alignment, particularly with current proposed changes to environmental legislation and offset requirements. The final report will be independent and made publicly available.

Overview of the Northern Jarrah Forest

Regional context

The Northern Jarrah Forest (NJF) is one of two subregions within the Jarrah Forest as categorised by the Interim Biogeographic Regionalisation for Australia (Thackway & Cresswell, 1995). It is 1,898,798.75 ha in size[1] and roughly triangular, extending from near Koojan in the north, and between Dardanup and Arthur River in the south (Figure 1). Latitudinal and longitudinal boundaries range from approximately 13°51'S to 33°30'S and 115°50'E to 116°50'E (Bell & Heddle, 1989).

The NJF lies within the Southern and Southwest Flatlands subcluster (Climate Change in Australia, 2024). This climatic characterisation has a Mediterranean climate typified by mild, wet winters caused by westerly winds and cold ocean currents, and hot, dry summers with dry air and clear skies caused by subtropical pressure cells (Climate Change in Australia, 2024; Rundel et al., 2016; Thackway & Cresswell, 1995).

[1] Data source: IBRA Subregion Australia Version 7.0 - PED

Figure 1. Map depicting the location of the NJF (red) within the Jarrah Forest bioregion (orange) and the Southern and Southwest climatic region (yellow) and South West Biodiversity Hotspot (pink)

Temperatures across the NJF range from an average minimum of 6°C in winter[2] to an average maximum of 33°C in summer[3] (BOM, 2024a, 2024b). Average rainfall is 800 mm per year[4], although there a trend of decreasing rainfall of 20–40 mm per decade since 1961 (BOM, 2024c). Rainfall influences both groundwater and streamflow, with reduced runoff and steep declines in groundwater following drier years causing a corresponding reduction in streamflow (Grigg and Kinal, 2020; Hughes et al., 2012).

The NJF is diverse in terms of geomorphology, soils and vegetation; the change in these attributes is primarily driven by rainfall, creating a gradient of decreasing moisture from west to east (Bell & Heddle, 1989; Shea & Herbert, 1977). Geomorphologically, the valleys in the western NJF are narrow, encouraging faster movement of water through streams than areas of the eastern NJF (Bell & Heddle, 1989; Shea & Herbert, 1977). Soils throughout the NJF are overall geologically stable with deeply weathered profiles (Wardell-Johnson et al., 2015). These soils are typically slightly acidic, dominated by quartz, and have low levels of nutrients (Hingston et al., 1981; Soltangheisi et al., 2023; Wardell-Johnson et al., 2015), however, there is a gradient of increasing salinity from west to east[5] (Figure 2) (Bell & Heddle, 1989; Shea & Herbert, 1977).

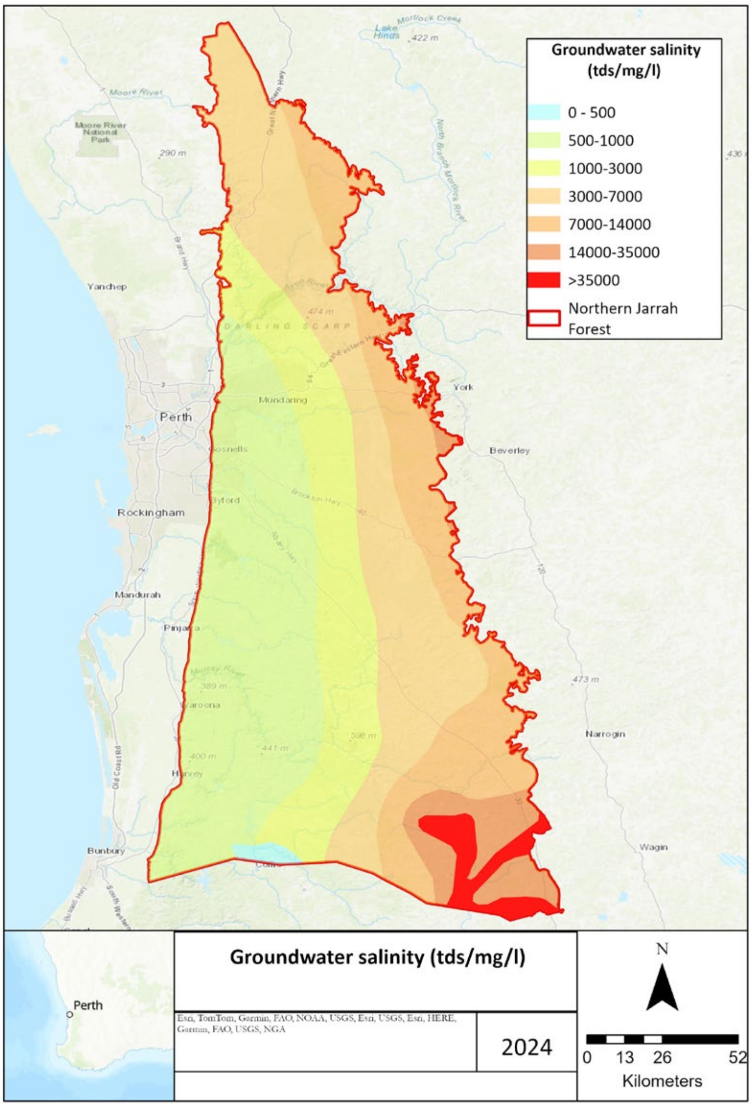

Figure 2. Gradient of salinity in the NJF (tds/mg/l)

[2] Data source: winter average daily minimum temperature graph between 1961 and 1990.

[3] Data source: summer average daily maximum temperature graph between 1961 and 1990.

[4] Data source: average annual rainfall graph between 1961 and 1990.

[5] Data source: Groundwater Salinity Statewide (DWER-026)

Broadly, the vegetation of the NJF is typified as an open canopy (>60%) dry sclerophyll forest with an overstorey dominated by jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*), and a diverse shrub and herbaceous understorey including *Allocasuarina fraseriana*, *Banksia grandis*, *Persoonia longifolia*, *Persoonia elliptica*, *Xanthorrhoea preissii*, *Kingia australis* and *Macrozamia riedlei* (Bell & Heddle, 1989, Daws et al., 2021a; Dell & Havel, 1989). Western areas tend to be dominated by jarrah-marri forest on laterite soils in elevated areas with bullich (*Eucalyptus megacarpa*) and blackbutt (*Eucalyptus patens*) in valleys (Shea & Herbert, 1977; Williams & Mitchell, 2001). In eastern areas, wandoo (*Eucalyptus wandoo*) and flooded gum (*Eucalyptus rudis*) are found on clayey soils and occur more frequently in elevated areas with powder bark (*Eucalyptus accedens*) and York gum (*Eucalyptus loxophleba*) in lower lying areas (Dell & Havel, 1989; Shea & Herbert, 1977; Thackway & Cresswell, 1995; Williams & Mitchell, 2001). Banksia woodlands are also found throughout the NJF on sandier soils (Williams & Mitchell, 2001).

History

Following European occupation, the NJF was managed for water yield and timber production (Harper et al., 2019) resulting in extensive clearing and, consequently, very little old growth forest remains (DBCA, 2019). However, the harvesting of native timber has now ceased and over time other industries have also utilised the Jarrah Forest (Figure 3). Large proportions of the NJF are used for agriculture or are within the conservation estate managed by DBCA (EPA, 2024b), however, many of these areas are also assigned as mining tenements for exploration and/or mineral extraction . Most of the high-quality stands of jarrah were removed before 1919 and by the mid-1960s most of the forest had been logged at least once (Abbott & Loneragan 1986; Havel et al., 1989). While some regeneration has occurred, there has been an overall change in structure of the NJF; from larger, wider spaced trees to higher densities of smaller trees (Daws et al., 2021a; DBCA, 2019; Havel et al. 1989).

[6] Data source: Mining Tenements (DMIRS-003)

1836

- Europeans occupy Northern Jarrah Forest (NJF) **(Pearce, 1982)**

1850

- NJF timber supports development of the Swan River Colony **(Mills, 1989)**

1918

- *Forest Act* passed – incl. forest land, prescribed burns and regeneration **(Havel, 1989)**

1921

- First reported patch death of Jarrah **(Dell & Malajczuk, 1989; Havel, 1989)**

1924–29

- State forest dedicated to NJF mostly on agricultural land (1,107,465 ha by 1929) **(Havel, 1989)**
- End of leases and concessions; forest management starts **(Mills, 1989; Havel, 1989)**

mid-1940s

- Softwood planting starts (esp. fertile valley slopes) **(Havel, 1989**

1950

- *Native Fauna Act* passed **(Havel, 1989)**

1955–56

- Timber use increases for industrial expansion in Perth **(Havel, 1989)**

1960–61

- Chemical weedicides developed; thinning increases **(Havel, 1989)**
- Prescribed burning starts in regenerated areas **(Havel 1989)**
- *Alumina Refinery Agreement Act* passed
- Mining lease granted to Alcoa **(Havel, 1989)**

1962–63

- Review of National Parks and Nature Reserves finds inadequacies **(Havel, 1989)**
- Alcoa starts mining at Jarrahdale **(Gardner & Bell, 2007)**

1963–65

- Dieback increases due to wetter than usual years **(Dell & Malajczuk, 1989; Havel, 1989)**
- *Phytophthora cinnamomi* identified as cause of dieback. Silviculture and logging change to prevent spread **(Havel, 1989)**

1966–67

- Alcoa starts mine rehabilitation (using exotic sp. and return of topsoil) **(Gardner & Bell, 2007)**
- WA economic boom — Perth population increases
- Timber, recreational spaces and bauxite demand in NJF increases **(Havel, 1989)**

late 1960s

- 'Virgin forest' declared (protected from logging) **(Havel, 1989)**
- Alcoa's Pinjarra refinery commissioned **(Alcoa, 2023)**

Figure 3. Timeline of uses and influences over the NJF

1970

- Risk of loss of Jarrah Forest identified by the Forest Department **(Havel, 1989)**
- Bauxite mining leases include almost all of the state forest in the NJF. Mineable bauxite reserves only constituted 3.5% of total area. Rehabilitation largely unsuccessful **(Havel, 1989)**

1971

- *Environment Protection Act* is passed **(EPA, 2021)**
- Alcoa establish Del Park mine for Pinjarra refinery **(Gardner & Bell, 2007)**

early 1970s

- Deep ripping soil introduced; vastly improves success of rehabilitation of mined areas **(Havel, 1989)**
- Thorough vegetation surveys; further virgin forest designated **(Havel, 1989)**

1975

- Understory species (esp. acacias) included in rehabilitation; improves waterways, reduces fertiliser use **(Havel, 1989)**

1976

- Alcoa starts mining at Huntly Bauxite Mine **(Alcoa, 2023)**
- Forest management changes following surveys; forest zoned into Management Priority Areas **(Havel, 1989)**

late 1970s

- Alcoa implement double stripping and direct return of topsoil for all rehabilitation **(Gardner & Bell, 2007)**
- Allowable cut for timber declines; timber harvest mostly for furniture instead of construction **(Havel, 1989)**
- *Forest Act* amended for better dieback control, esp. eastern area of NJF, due to higher salinity risk **(Havel, 1989)**

1978

- Worsley propose bauxite mine near Boddington **(Havel, 1989)**

1981

- System 6 report to Environmental Protection Authority (EPA) recommends conservation areas; however water catchments and bauxite mining concerns override changes **(Havel, 1989)**

1982

- EPA requires Alcoa to protect flora and fauna, limit expansion and submit mining and management programs for approval **(Havel, 1989)**

1984

- Mining starts at Alcoa's Willowdale Bauxite Mine **(Alcoa, 2023; Gardner & Bell, 2007)**
- Research into heavy thinning in high-rainfall catchments with low salinity conducted (but not implemented) **(Havel, 1989)**
- Alcoa's Wagerup Refinery is commissioned **(Gardner & Bell, 2007)**

1985

- Worsley receive approval to mine and process ore at the Boddington Gold Mine **(Ministerial Statement 085)**

1986

- *Environmental Protection Act 1986* is introduced **(EPA, 2021)**

1988

- Alcoa gain approval and start operations at Hedges Gold Mine **(Ministerial Statement 020; Alcoa, 2023)**
- Approval of Briquette plant at Collie **(GWA, 1988)**

1970 · 1975 · 1980 · 1985 · 1990

Figure 3. Timeline of uses and influences over the NJF (continued)

1990

- EPA invite first public comment on development proposals **(EPA, 2021)**

1992

- Approval of Ewington coal mine **(GWA, 1992a)**
- Approval of Premier Coal Mine expansion **(GWA, 1992b)**

1993

- Boddington gold mine extended (**GWA, 1993)**

1998

- Alcoa's Jarrahdale mine closed; final restoration commences, incl. planting of recalcitrant sp. (**Gardner & Bell, 2007)**

1999

- Alcoa complete operations at Hedges Gold Mine **(Aloca, 2023)**

2001

- Alcoa completes restoration at Jarrahdale Mine **(Gardner & Bell, 2007)**
- WA Government decides to end old growth logging **(GWA, 2024)**

2002

- Alcoa starts thinning and burning trials **(Gardner & Bell, 2007)**
- Construction and operation of a gas fired power station at Boddington Gold Mine approved **(GWA, 2002)**

2004

- Alcoa's McCoy operations facilities commissioned at Huntly Mine **(Gardner & Bell, 2007, Alcoa, 2023)**

2005

- Aloca hands back 975 ha of restored land at Jarrahdale to CALM **(Gardner & Bell, 2007)**

2006

- Approval of Bluewaters coal-fired power station near Collie **(GWA, 2006)**

2009

- Newmont start gold and copper mining at Boddington Gold Mine **(Newmont, 2024)**

2021

- WA Government announce end to commercial logging in native forests **(GWA, 2024)**

2022

- Worsley Mine Expansion Environmental Review Document circulated for public comment **(Worsley, 2022)**

2024

- Commercial native logging ends in WA **(GWA, 2024)**

1990 1995 2000 2005 2010 2015 2020 2025

Figure 3. Timeline of uses and influences over the NJF (continued)

Environmental value

The NJF is one of several bioregions situated within the South West Biodiversity Hotspot (see Figure 1); one of 36 biodiversity hotspots found globally. Biodiversity hotspots are areas with biological commonalities and both high endemism (>1,500 endemic vascular plants) and risk of loss (30% or less of original vegetation) (CI, 2024, Myers et al., 2000). The South West Biodiversity Hotspot includes 13 endemic plants and 0.3 endemic vertebrates per 100 km^2 (Myers et al., 2000). Biodiversity hotspots are of global significance; together they comprise less than 3% of the worlds surface but contain more than 40% of biodiversity and 35% of ecosystem services (Habel et al., 2019). Given that biodiversity hotspots have a greater proportion of the worlds threatened species, the protection and restoration of biodiversity hotspots is of key importance for conservation (Myers et al., 2000).

There are three nationally important waterways within the NJF, the Wannamal Lake System (WA094) in the Swan-Avon catchment, the Avon River Valley (WA045) and the Chittering-Needonga Lakes (WA047) (DBCA, 2018; DCCEEW, 2024b). All three waterways are within the Brockman catchment, which is a key source of water for the Perth metropolitan area (Shea & Herbert, 1977). Further, most of the NJF has been proclaimed under the *Rights in Water and Irrigation Act 1914* (RiWI Act)[7] (Figure 4a). There are also small areas that are proclaimed for ground water management in the west of the NJF. Use of water from areas proclaimed under the RiWI Act require a license or permit from the Department of Water and Environmental Regulation (DWER). A large proportion of areas within and adjacent to the west of the NJF are also within Priority 1 Public drinking water source areas[8]; these are public lands where "the provision of high-quality public drinking water is the prime beneficial land use" (DoW, 2009). There are also priority public drinking water source areas to the west of the NJF (Figure 4b).

Approximately 45% (863,154 ha) of the NJF is currently managed by the Western Australian Department of Biodiversity, Conservation and Attractions (DBCA) as either part of the conservation estate or as government owned freehold land[9]. However, less than 2% (33,877 ha) of the remaining NJF is considered old growth forest, all of which is managed by DBCA (EPA, 2023b). There is a further 9% (161,890 ha) that has been identified by DBCA for inclusion in the conservation estate, but not yet formalised[10] (Figure 4c). Additionally, a report developed by the Beeliar and Leeuwin groups has identified more than 200,000 ha as conservation areas (including those identified by DBCA) for further protection of priority ecological values in the NJF, including rare and threatened flora and fauna, waterways and old growth forests (Martin et al., 2022).

A protected matters search[11] of the NJF yielded eight threatened ecological communities, 125 listed threatened species and 9 migratory species (Appendix 1). There are 602 records of priority ecological communities in the NJF and 34,480 ha of priority and threatened ecological communities listed under the Western Australian *Biodiversity Conservation Act 2016*[12] (Figure 4d).

Jarrah trees are the most dominant and consistently found plant species across the NJF. They are a slow growing species (1–2 cm per year) growing to 30–40 m in the subregion, and straight, with a width of approximately 2 m diameter (Dell & Havel, 1989). In addition to jarrah, the forest retains a diverse floral assemblage (Bell & Koch, 1980; Grant & Koch, 2007), with some surveys undertaken in the southern area of the NJF identifying 899 native plant species (Mattiske, 2010). Understorey diversity is also high, with reports of 400–600 species per km^2 (Daws et al., 2021a), as are fungi (Glen et al. 2008).

The NJF is also a key habitat for many fauna species, with estimates of more than 200 vertebrate species (Grant & Koch, 2007). Invertebrate diversity has been less studied but thought to include currently undescribed species and to be in the order of tens of thousands (Grant & Koch, 2007).

[7] Data sources: RIWI Act, Groundwater Areas (DWER-034); RIWI Act, Surface Water Areas and Irrigation Districts (DWER-037)

[8] Data source: Public Drinking Water Source Areas (DWER-033)

[9] Data source: DBCA - Legislated Lands and Waters (DBCA-011)

[10] Data source: Forest Management Plan (FMP) 2024 - 2033 (DBCA-078)

[11] Department of Climate Change, Energy, the Environment and Water Protected Matter Search Tool, results within the NJF region (no buffer), accessed on 7/05/2024 (https://www.dcceew.gov.au/environment/epbc/protected-matters-search-tool#toc_0)

[12] Data source: Threatened Ecological Communities (DBCA-038)

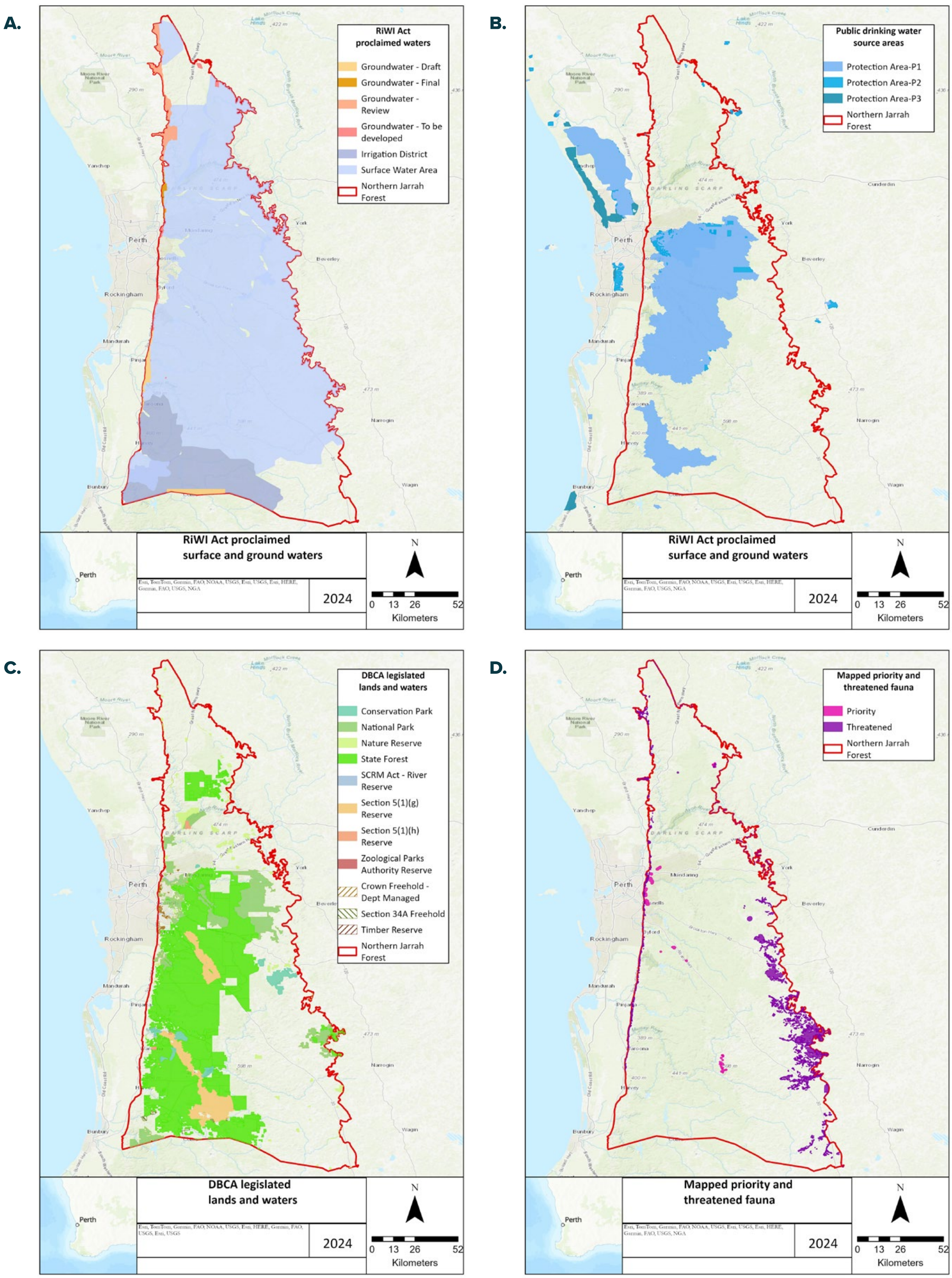

Figure 4. Designated areas within the NJF a) Proclaimed ground water, surface water and irrigation areas under the RIWI Act; b) Public water source areas within and adjacent to the NJF; c) Lands managed by DBCA within the Conservation Estate and as freehold; d) Approximated distribution of known priority and threatened ecological communities across the NJF

Cultural value

Aboriginal people have inherited rights to particular tracts of land and a long history of active land management across the South West of Australia, including in the NJF (Lullfitz et al., 2017; SWALSC, 2024). The recent Southwest Native Title Settlement has reassigned areas of the NJF to the Noongar land estate, enabling regional corporations representing the Traditional Owners of these lands (Yued, Whadjuk, Ballardong and Gnaala Karla Booja Aboriginal Corporations) to lease areas from within this estate for cultural, social and economic purposes (SWALSC, 2024). In addition, there are more than 600 registered Aboriginal sites within the NJF, including several rivers as depicted by Figure 5a[13]. There is also one listed National Heritage site, the Goldfields Water Supply Scheme (pipeline), and one listed Commonwealth Heritage site, Bindoon Defence Training Area (DBCA, 2019). No World Heritage sites are found within the NJF (DBCA, 2019).

While earlier accounts stated that the NJF was seldom used by Aboriginal people, a cultural heritage survey conducted in 1980 found many Aboriginal artefacts throughout an area of the NJF (Pearce, 1982). Since this time, further cultural heritage surveys have been conducted throughout the region (e.g. Archae-aus, 2022; Winton, 2021), and the significance of the NJF to Aboriginal people has become more broadly recognised (Flynn & Ugle, 2023; Lullfitz et al., 2017; SWALSC, 2024).

Across the South West, Aboriginal people have used fire for game attraction, plant resource renewal and maintaining access to country; managed and protected perennial and annual species; and modified habitat and increased the geographical extent of species to improve access to resources (Lullfitz et al., 2017). Burning, in particular, is an important management tool and was employed when seasonal, weather and vegetation conditions were suitable (Ruane et al., 2018). In the NJF, like elsewhere in the South West, this was usually conducted in summer (Ruane et al., 2018). In addition, plant species and habitat variation have important cultural significance to Aboriginal people as part of restrictive law and territorial markers, as well as contributing to cultural values through the use of certain species as totems, a part of Noongar lore (Lullfitz et al., 2017; SWALSC, 2024).

Aboriginal people inhabited the NJF in alignment with seasonal and climatic changes throughout each year (Pearce, 1982; Pearce, 1989) and were instrumental in European settlement, teaching early settlers to the Swan River colony fire stick burning, and the locations of water holes and access paths (Mills, 1989). However, much of this traditional knowledge was lost due to concerns from early settlers regarding fire practices in the mid-1800s, particularly in the grassy areas surrounding the NJF, and the huge reduction in Noongar populations in the late 1800s and early 1900s due to from disease (Ward, 1998). Aboriginal lore is closely tied to the principles of conservation (SWALSC, 2024) and their Traditional knowledge and insight can improve restoration and conservation management.

Socioeconomic value

The NJF has had a long history of economic significance in Western Australia. European occupation of the NJF commenced in 1836 and supply of timber from the forest was a key feature of the establishment of the Swan River Colony (Mills 1989; Pearce, 1982). Over time, the dominant industries within the NJF have changed, with mining, in particular, becoming more important. Other emerging uses include beekeeping, conservation and recreational activities such as hunting, horse riding, hiking, mountain and dirt bike riding, and four-wheel driving (DBCA, 2019; Subroy et al., 2021).

Mining

There are extensive areas designated for mining and exploration across the NJF (Figure 5b)[14], and mining leases cover the majority (79%)[15] of the region (EPA, 2024b), however, only a small proportion of these areas contain basic raw materials for construction (Figure 5c). The mining industry provides economic benefit to Western Australia through sales, employment and royalties. Proportionally, the mining industry in Western Australia contributes almost 60% of the gross value from mining across Australia (DJTSI, 2023a).

The mining industry is the fifth largest employer in Western Australia, employing approximately 7.5% of workers across more than 3,000 mining businesses (ABS, 2024). Mining, and the industries they support, are the largest contributor to Western Australia's gross state product (GSP) contributing $186.8B, approximately 46% of total GSP, in 2021-22 (DJTSI, 2023a). Bauxite mining, the dominant mining industry in the NJF, contributed approximately 3.6% of mining sales in 2021-22 (DJTSI, 2023a), and employed approximately 0.5% (7,700 people) of all workers across the state (Alcoa, 2024a; GWA, 2024; IBISWorld, 2024; South32, 2024).

Royalties are required by the Western Australian Government through either State Agreements or as prescribed by the *Mining Act 1978* (Department of Treasury, 2023). Over the last 10 years, royalty collections in WA for bauxite/alumina have increased from $81.8M to $114.8M annually and for gold have increased from $228.7M to $544.4M (Department of Treasury, 2023), representing approximately 0.6% of all taxes and royalties collected annually by Western Australia and 0.3% of Western Australia's GSP (Department of Treasury,

[13] Data source: Aboriginal Cultural Heritage Register (DPLH-099)

[14] Data source: Mining Tenements (DMIRS-003)

[15] Data source: Mining Tenements (DMIRS-003)

2023; DJTSI, 2023a). In addition to royalties, mining companies operating under the *Mining Act 1978* provide funding towards rehabilitation of abandoned mine sites under the Mining Rehabilitation Fund (MRF) (Department of Treasury, 2023). Mining companies operating under State Agreement Acts are exempt from this requirement unless it is explicitly required in the State Agreement, although may contribute to the MRF on a voluntary basis. Between July 2015 and June 2024, Western Australia has collected rehabilitation levies between $27.8M and $40.9M per year (Department of Treasury, 2023). Mining companies may also be required to make other financial contributions under State Agreements or other mechanisms.

Forestry

Timber harvesting in Western Australia is undertaken by the Forest Products Commission. The contribution of timber harvesting to Western Australia's economy has decreased over time (DJTSI, 2023b). The Forest Products Commission (FPC) also has a low employment rate, with 185 employees in 2022-23 (FPC, 2023).

Native forestry, typically timber from jarrah, marri or karri, has also decreased consisting of 8% of the forestry industry as a whole (DJTSI, 2023b; FPC, 2023). For example in 2023, the income from native forest products, including from the NJF, was $32.6M, but income from plantations was $85.9M (FPC, 2023). However, timber from native forestry has since ceased, with the only timber now permitted to be removed resulting from forest management activities (e.g. thinning) or associated with clearing for approved developments (DJTSI, 2023b).

Agriculture

Approximately 748,510 ha[16] (40%) is potentially arable land (Figure 5d), however, more than half of this area (411,414 ha) intersects with mining tenements, particularly in the north, and therefore it is unknown how this land is used.

Although cleared by early European settlers for agricultural purposes, the NJF is no longer recognised as a key agricultural area. However, it lies to the west of the Wheatbelt region, which is the region that generates approximately 68% of agricultural income in Western Australia, predominantly from broadacre crops (DPIRD, 2021).

Other

The tourism industry generates $8.7B (~2%) to Western Australia's GSP, and provides 89,100 jobs (TWA, 2023). Specifically, 'Destination Perth', that includes the NJF as well as the Perth and Peel regions, generated 30,800 jobs (2.5% total WA jobs) and $2,229M (0.9% GRP) in 2021-22 (TWAIP, 2023).

There were 3,524 beekeepers registered in Western Australia in 2020 representing 15% of all beekeepers in Australia, but only 7% of all hives (White & Day, 2022). Commercial hives are moved regularly mostly between sites on public land such as unallocated crown land, state forest, reserves and national parks (White & Day, 2022). There are 913 apiary sites held across the NJF which yield $0.9M (White and Day, 2022). Honey produced from the Jarrah Forest region is sought after and attracts a significantly higher premium (White and Day, 2022).

Seed harvesting in Western Australia has increased rapidly from <5000 kg in 2000 to almost 50,000 kg in 2015 (DBCA, 2019). This is likely to increase with new demands to meet state and Commonwealth conservation goals. The cost of Australian native seed is relatively expensive at $1,093 per kg on average, with overstorey species generally less expensive (~$570 per kg) than understorey species (>$1,500 per kg) (Pedrini et al., 2022).

[16] Data source: Potentially Arable Land (DPIRD-026)

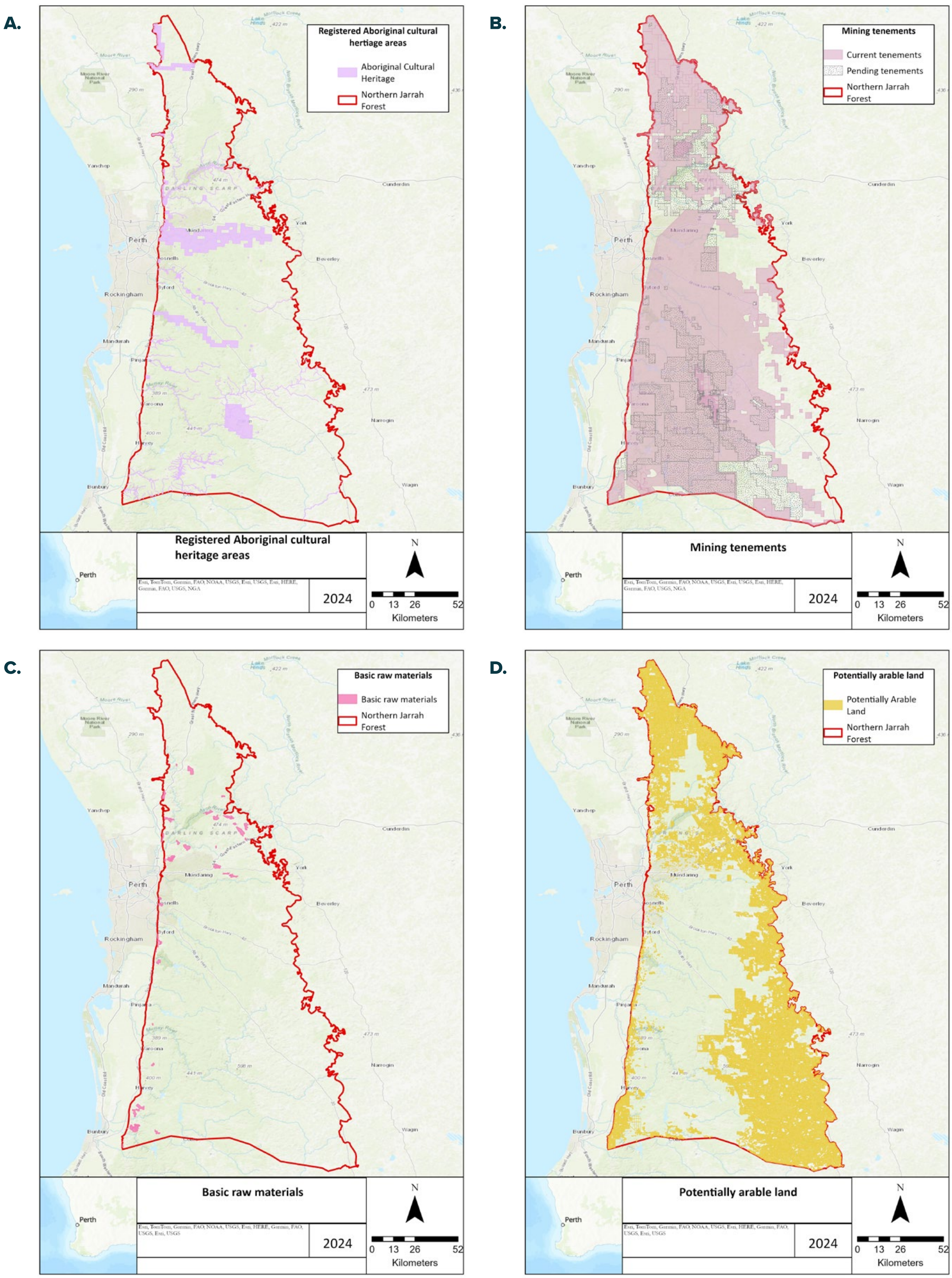

Figure 5. Areas of cultural and socioeconomic significance in the NJF a) Registered Aboriginal Heritage sites; b) designated mining and exploration areas; c) regionally significant areas for raw materials; d) potentially arable land

Associated regulation and management commitments

Western Australian

Western Australia Department of Biodiversity, Conservation and Attractions (DBCA) are responsible for the conservation and management of the conservation estate and other government owned lands. In the NJF, this represents approximately 45% of region. However, conservation activities are also undertaken in a voluntary capacity in other parts of the NJF by community groups, Aboriginal Corporations and private landholders on their private land, and developers may be required to undertake environmental offsets to compensate for significant residual impacts of development on the environment (Figure 6).

Forest Management

The *Forest Management Plan 2024–2033* (Forest Management Plan) describes the range of management activities that are planned to be undertaken by DBCA to protect and manage forest values across the South West (CPC, 2023). The Forest Management Plan describes four strategic goals for forest management:

1. to value and protect Noongar cultural heritage and support Noongar Traditional Owner involvement;
2. to conserve biodiversity and support ecosystem resilience;
3. to maintain or improve forest health and enhance climate resilience; and
4. to deliver social, cultural and economic benefits through the provision of goods and services (CPC, 2023).

The NJF overlaps two DBCA geographic regions identified by this plan, the Swan region and a portion of the South West region.

State Agreements

Historically, mining and resources projects in Western Australia have been implemented under State Agreements, contracts between the government and a resources company that have legislative approval (Southalan, 2023). In Western Australia, State Agreements are widely used; around 80% of the value of extractive resources across the whole state are operated under State Agreements (Southalan, 2023). In the NJF, there are 6 (of 64) State Agreements currently in effect covering alumina, charcoal iron and steel, and coal industries (DJTSI, 2020; Southalan, 2023). State Agreements, which are administered by the Department of Jobs, Tourism, Science and Innovation (JTSI), and enacted by the *Government Agreements Act 1979*, provide regulation for activities where existing laws are inadequate or inappropriate (Southalan, 2023). As such, most extractive proposals are now assessed and regulated under the *Environmental Protection Act 1986* (EP Act).

Threatened species and ecological communities

Western Australian threatened species and ecological communities are listed under the *Biodiversity Conservation Act 2016* (BC Act). DBCA have the responsibility for the protection and conservation of listed species and ecological communities. While DBCA may require offsets for the taking of listed species under the BC Act, ecological communities or associated impacts to critical habitat, offsets are usually required by the Environmental Protection Authority (EPA) that has the responsibility for approval of activities that may significantly impact the environment, including listed species and ecological communities.

Native vegetation clearing

The clearing of native vegetation in Western Australia, including within the NJF, is regulated under the EP Act. There are three government departments that administer approvals related to clearing under this Act:

- the Department of Water and Environment Regulation (DWER) assesses applications for clearing permits under Part V of the EP Act. Applications for Part V clearing permits are approved only where the impact from clearing is considered very low;
- the Department of Energy, Mines, Industry Regulation and Safety (DEMIRS) have a delegated authority from DWER to approve Part V clearing permits on areas to be mined;
- the Environmental Protection Authority (EPA) assess applications for clearing that are likely to result in a significant environmental impact under Part IV of the EP Act (DWER, 2021a).

Mining activities, including the environmental management and rehabilitation of mine sites, are further regulated by DEMIRS under the *Mining Act 1978*. DEMIRS also may require mining securities; unconditional performance bonds that ensure environmental conditions and remediation following mine closure will be met should a company be unable to meet their related obligations (DEMIRS, 2020).

Commonwealth

The Commonwealth has the responsibility for the protection of Matters of National Environmental Significance (MNES) across Australia, including threatened species and ecological communities, and migratory species under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). However, the management of Commonwealth forests in Western Australia is delegated to DBCA (CPC, 2023). The Commonwealth does not regulate the clearing of native vegetation except where it impacts threatened species or ecological communities. Any activities that are likely to have a significant direct or indirect impact on MNES require approval by the Minister for the Environment (or their delegate) under the EPBC Act through assessment by the Department of Climate Change, Energy, the Environment and Water (DCCEEW).

International commitments

Australia has committed to the conservation of biological diversity as a signatory to the Convention on Biological Diversity and its goals for sustainable development as stated in the Global Biodiversity Framework. The Global Biodiversity Framework has four key goals: to protect and restore nature, to ensure the sustainable use of biodiversity and natures contribution to people (ecosystem functions and services), to ensure the benefits of nature are shared fairly and equitably, and encourage investment in nature and technical and scientific collaboration (CBD, 2024a). These goals are of relevance to the conservation and uses of the NJF.

In addition, Australia has agreed to ensure sustainable development through commitment to the international agreements United Nations Agenda 21, the Rio Declaration on Environment and Development, and the 2030 Agenda for Sustainable Development (including the Sustainable Development Goals). Further, Australia has implemented Australia's strategy for nature, with goals to support healthy and functional ecosystems by connecting people with nature, caring for nature in all its diversity and sharing and building knowledge (CoA, 2017). Ensuring the balance of socioeconomic priorities and environmental values is of key importance for areas of environmental significance such as the NJF.

Environmental offsets

Environmental offsets (also known as biodiversity offsets) are a mechanism used to balance the implementation of sustainable development. as they provide a way to enable the environmental impacts of development to be compensated. However, their effectiveness over time has been questioned, with several reviews finding offsets lacking in their ability to deliver adequate compensation (Abdo, 2023). For example, zu Ermgassen et al. (2019) found that offsets undertaken in forested ecosystems did not deliver adequate compensation for biodiversity from a metanalysis of more than 15,000 documents from various locations globally. Similarly, May et al. (2017) reported that 30% of offsets required in Western Australia between 2004 and 2015 were unsuccessful in achieving expected outcomes. In a different study, zu Ermgassen et al., (2023) found that loss and degradation of native vegetation in Victoria was only slightly (>4 per year) compensated for by restoration offsets and that there was no detectable impact of compensation from protection offsets. Regardless, if implemented strategically, biodiversity offsets have the potential to deliver both compensation for impacts and a contribution to the goals of sustainable development (Abdo, 2023).

Strategic approaches to offsets can ensure that offsets contribute to benefits for all aspects (environmental, economic, social) of sustainable development (Bull et al., 2019). Strategic choice of offsets sites can also provide better outcomes for individual species (Rhodes et al., 2023).

Western Australian

The Government of Western Australia allows environmental offsets to be undertaken to compensate for significant residual impacts related to Part IV and Part V applications under the EP Act (EPA, 2014). Environmental offsets are only permitted after the environmental impacts of native vegetation clearing have been avoided and minimised wherever possible (EPA, 2014). Further, these environmental offsets are required to contribute to Western Australia's broader conservation objectives (EPA, 2011), although, other than those identified in the Forest Management Plan (CPC, 2023) to be undertaken on public land, no other conservation objectives have been published to date.

Environmental offsets are utilised for the contribution to sustainable development in every jurisdiction in Australia, however, there is a lack of consistency between the rules which apply to offsets between each jurisdiction (Table 1) (Abdo, 2023).

The environmental offset framework has been in place in Western Australia since 2011, and in 2019, DWER undertook a review of this framework (DWER, 2019). The review found that the implementation of offsets was lacking, and provided several recommendations, including revisions to the offsets policy, guidelines and register, finalisation of the offset calculator, updates and ongoing review to the operational procedures and metrics for offset fund contributions, and the development of bioregional plans to support the development and implementation of offsets (DWER, 2019). The offset calculator was finalised in 2021 (DWER, 2021b) and the EPA has provided public advice regarding offsets at a regional scale (EPA, 2024a).

The public advice provided by the EPA encourages a regional approach to restoration and management that consider the enhancement and restoration of environmental values, improvement of ecological linkages and ecological connectedness (EPA, 2024a). In addition, the EPAs public advice provides a more flexible approach, providing for consideration of like-for-similar offsets and co-benefits with heritage cultural and social values (EPA, 2024a). This is a lesser utilised approach that has been shown to balance the social and economic aspects, having potential benefits for sustainable development (Abdo, 2023). The need for regional planning and mapping of holistic values (species, ecological values, functions and performance) are also highlighted (EPA, 2024a).

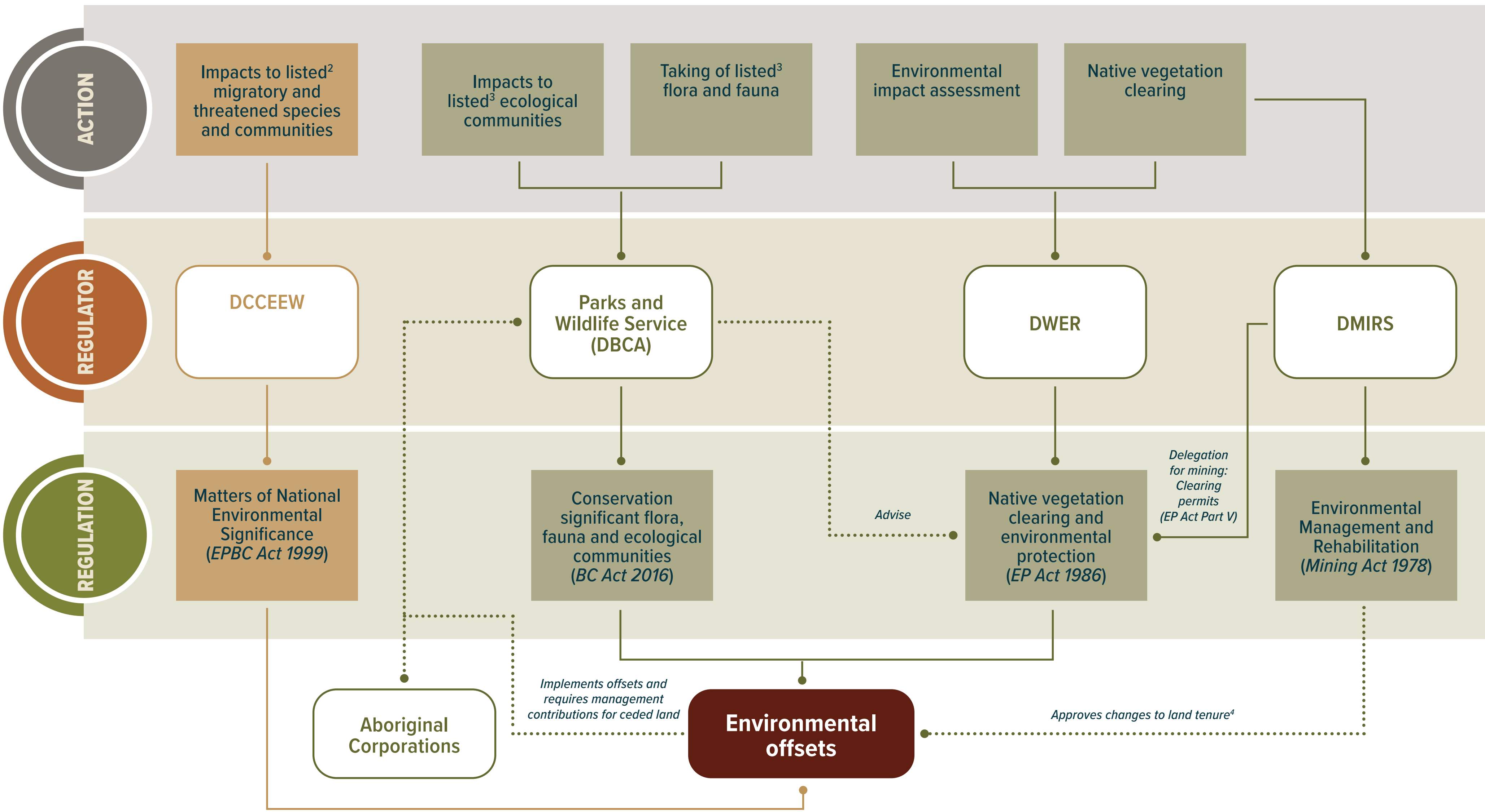

Figure 6. Significant residual impacts in the Northern Jarrah Forest[1]

1. Significant residual impacts means environmental impact remaining after all avoidance and mitigation measures have been fully explored and is consistent with both the description of "Significant Residual Impacts" in the WA Environmental Offset Guidelines (EPA, 2014) and the description of "Residual Significant Impacts" in the Environment Protection and Biodiversity Conservation Act 1999 Environmental Offsets Policy (DSEWPaC, 2012).
2. Species and ecological communities listed as Matter of National Environmental Significance in the Environment Protection and Biodiversity Conservation Act 1999
3. Threatened and priority flora, fauna and ecological communities, and critical habitat as listed in the Biodiversity Conservation Act 2016
4. DMIRS has a role in the approval of changes to land tenure (e.g. covenants) that are often required to provide legal protection of offset areas

Table 1. Summary comparison of offset requirements in different jurisdictions around Australia. Requirements marked by '–' indicate that no mention was made in associated offset policies

		Commonwealth		WA			ACT	NSW	NT	Qld	SA	Tas	Vic
		Current policy	Proposed changes Mar24	Current policy	Current guidelines	EPA public advice	Current policy	Guidance	Current policy	Current policy	Current policy	Current policy	Current guideline
Requirements	Purpose/matter	MNES		Environmental values			MNES and ACT protected species	Biodiversity	Biodiversity	Environmental matters	Native vegetation	Environmental values	Native vegetation
	No net loss of purpose/matter required	Requires	Yes	–	Requires	–	Requires	Aims to achieve	–	Yes	–	–	Yes
	Net gain of purpose/matter required	Allows	Yes	–		–	Allows	–	Requires	–	Requires	–	–
	Advanced offsets permitted	Yes	Yes	–	Yes	Yes	Yes	–	No	Yes	Yes	–	–
	Sustainable development/ socio-economic priorities considered	Yes	Yes	–		Yes	–	–	–	–	–	–	–
	Stakeholder engagement required	–	Yes	–	Yes	–	–	–	Yes	–	–	–	–
	Payments/funds permitted	Yes	Yes	–	Yes	–	–	Yes	No	Yes	Yes	–	Yes
	Offsets can be located in other bioregions	–	Yes	–	–	–	Yes	No	No	Only if adjacent	No	Yes	No
	Like-for-similar permitted	–	No	Yes	Yes	Yes	No	Yes	–	–	Yes	–	–

DWER is currently reviewing further offset documentation for the reform of offset policy and guidelines including consideration of offset funds (DWER, 2021c). Further, DWER is also undertaking a regional planning process (DWER, 2021c).

According to the publicly available register of offsets[17], to date there have been 25 referrals that overlap NJF, 14 referrals for projects solely in the NJF (approved project area 181.47 ha), and 11 for projects that also extend across other bioregions (11,639.7 ha). There are 13 referrals that have completed their offsets in the NJF, all through land acquisition (1,357.5 ha). Conversely, there are 16 referrals yet to complete offsets in the NJF, of which there will be four land acquisition offsets (404.1 ha), 11 rehabilitation offsets (169.42 ha), and one 'other' offset (6 ha). In addition, there are nine referrals for projects that overlap the NJF but have/will undertake offsets in other bioregions (2,620.13 ha).

While the Environmental Offsets Policy allows for offsets to be considered under the *Mining Act 1978* or the *Planning and Development Act 2005*, this has not been undertaken to date. Ceding of land into the conservation estate or the application of a conservation covenant is a common way to achieve offset protection and permanence criteria. Land is ceded into the conservation estate is thereafter managed by DBCA, and therefore, DBCA must agree to accept the tenure and management of offset land prior to the finalisation of offset conditions. While it is possible for land to be ceded to Aboriginal Corporations, in order to ensure ongoing funding for land management, there needs to be allowances for activities on that land to generate income. The implementation of specific exemptions to enable economic productivity that is not inconsistent with the protection of environmental values at the offset site (e.g. managed seed collection, honey production) may therefore need to be included in the protection mechanism (i.e. covenant).

The intention of ceding land into the conservation estate is for the creation of a conservation reserve under the *Land Administration Act 1997*. However, the creation of a conservation reserve requires the approval of DEMIRS (CCWA, 2011). Land ceded to the conservation estate, but not as a conservation reserve, is typically unmanaged (CCWA, 2011). It should be noted that conservation reserves do not legally exclude exploration or extraction of resources, although native title rights and interests are extinguished (CCWA, 2011). Similarly, conservation reserves do not exclude mining or native title and, therefore, discussion and agreement with DEMIRS and Aboriginal Corporations are suggested prior to the finalisation of offset conditions.

Commonwealth

Where significant impacts on MNES can't be avoided, there is an expectation by the Commonwealth that environmental offsets will be undertaken to compensate for these impacts (DSEWPaC, 2012). Since 2001, there have been 123 EPBC Act referrals relevant to the NJF, including 26 for mining, of which 17 were withdrawn, 1 had lapsed and 17 had received an approval decision with conditions requiring offsets under the EPBC Act[18] (Table 1).

[17] Data source: : Offsets Register – Offsets (DWER-078)

[18] Department of Climate Change, Energy, the Environment and Water Protected Matter Search Tool, results within the NJF region (no buffer), accessed on 7/05/2024

Table 2. Summary of offset actions required for referrals for projects within the NJF approved with conditions

		Industry			
		Mining	**Residential**	**Transport**	**Waste Management**
	Total referrals with offset conditions per industry	**7**	**3**	**6**	**1**
Offset actions	Payment to government for land acquisition and/or research	2	3	2	
	Cede offset land to government entity				
	Land acquisition	2		1	
	Land protection (covenant)	5	1	1	
	Revegetation and/or restoration	4		1	1
	Land management	1	1	2	1
	Installation of artificial hollows for black cockatoos	2		3	
	Offset plan (action not yet specified)			2	

In 2020, two reviews of the EPBC Act were published: an independent review of the EPBC Act (as required by the EPBC Act) and an Audit of referrals, assessments and approvals of controlled actions under the EPBC Act (ANAO, 2020; Samuels, 2020). These two reviews reported similar results, that the EPBC Act was lacking in its effectiveness to provide protection of ecosystems and biodiversity. As environmental offsets are required to provide biodiversity and ecosystem benefits, the outcomes of these reviews also have a direct bearing on offsets. As a consequence, DCCEEW is undertaking reform of the EPBC Act (DCCEEW, 2024c). These reforms seek to address the recommendations of these reviews by 1) establishing the Nature Repair market and expanding the water trigger; 2) establishing an independent regulatory body (the Environment Protection Australia) and a national environmental data agency, Environment Information Australia; 3) reform environmental laws including the development of national environmental standards, regional plans and the reform of offsets (DCCEEW, 2024c). As of June 2024, DCCEEW have completed the first stage and introduced the second stage to parliament (DCCEEW, 2024c). A timeline for the third stage has not yet been made publicly available, however some public consultation has been completed.

From this public consultation, several changes to offsets have been proposed including:

- a change in terminology from environmental offsets to 'restoration actions and restoration contributions;'
- allowance of restoration contributions, financial contributions to a fund governed by DCCEEW that will be made in lieu of offsets, and development of a restoration contributions tool to quantify the contribution;
- a requirement for restoration actions (i.e. protection and restoration offsets) to be commenced prior to environmental impact from development;
- requirements for community engagement and consultation (DCCEEW, 2024d).

While these changes have been proposed, they are yet to be finalised or to be approved by parliament. It is expected that this process could be lengthy and therefore a level of uncertainty around offset design and approval may pervade in the interim.

Key pressures

Australia's climate is changing. Across southern areas of Australia average temperatures and sea levels are increasing, while conversely, rainfall and streamflow are decreasing (CSIRO & BOM, 2022). Climate models, accounting for individualistic responses by native species and assuming a doubling of carbon dioxide within the next century, have predicted up to 23% of species from the South West Biodiversity Hotspot, which includes the NJF, may become extinct due to the impacts of global warming (Malcolm et al., 2006). Declining rainfall and subsequent disconnection of the water table from stream systems is the greatest threat to the Jarrah Forest (Burrows et al., 2011).

Agricultural clearing, changed fire regimes and predation by foxes and feral cats, have been found to be further significant pressures on threatened mammals in the Jarrah Forest (Calver & Dell, 1998a). Similarly, key pressures for threatened bird species were agricultural clearing and grazing by livestock, changes to fire regimes and the draining of wetlands (Calver & Dell, 1998a).

Climate change

The NJF is within the Southern and South-Western Flatlands West climate projection subcluster; the maximum and minimum temperatures of this region are projected to increase across all seasons with more hot days, longer warm spells and fewer frosts (Climate Change in Australia, 2024). A continuation of the decreasing trend in rainfall is also expected with corresponding longer periods in drought, although the intensity of extreme rainfall events is predicted to increase (Climate Change in Australia, 2024). Harsher fire weather is also expected (Climate Change in Australia, 2024). Therefore, the conservation of water and resilience to both fire and drought are primary considerations for the entire Southern and South-Western Flatlands West, including the NJF.

In southwestern Australia, winter rainfall has decreased by 15% since 1970, with the peak period of rain (May–July) showing a greater decrease of 19% (CSIRO & BOM, 2022). This has caused a decline in streamflow and a change from perennial to ephemeral streams (Petrone et al., 2010). Winter rainfall is predicted to decrease further over the coming years: 15% by 2030 and 25–45% by 2090 (DJTSI, 2023b). Drought severity and duration are also predicted to increase, along with larger fluctuations in summer rainfall events (DJTSI, 2023b).

The effects of climate change on vegetation density in the Jarrah Forest are already evident (Croton et al., 2014). Over the past 40 years, the Jarrah Forest has displayed a trend of increasing mean temperature by 0.15–0.30°C per decade (BOM, 2024d). The trend of decreasing rainfall over this period is a loss of 20–60 mm per decade (BOM, 2024e) and over the last 20 years, rainfall across the region has been the lowest on record (BOM, 2024f). The International Panel on Climate Change recently identified (with a high level of confidence) that the NJF has reduced resilience and adaptive capacity and there is a moderate risk that it will transition or collapse from hotter, drier conditions and increased fire risk (Lawrence et al., 2022). This risk will likely increase with increasing effects of changing climate.

Droughts can cause severe mortality and a structural shift in NJF structure with smaller, denser trees and multi-stemmed individuals replacing larger older trees (Matusick et al, 2016; Standish et al., 2015). Additionally, drought induced mortality has been found to disproportionately impact different species (Steel et al., 2019), changing species composition and potentially altering ecosystem functions and services of the NJF. Mortality of the overstorey can also have a negative effect on seedling emergence (Stoneman & Dell, 1994), impacting the ability for the forest to recover from heatwaves. While there is some evidence that jarrah trees are resilient to the effects of climate change and can recover from the impacts of severe drought (Standish et al., 2015, Macfarlane et al., 2018), widespread die off of jarrah due to hot and dry conditions was observed between 2010 and 2011 (Fontaine et al., 2024; Matusick et al., 2023). This resulted in the death of 19% of trees and shrubs within the affected areas and an overall loss of approximately 16,000 ha of forest canopy, with likely negative impacts on associated fauna species (Fontaine et al., 2024; Matusick et al., 2023). Forest die offs also increase fuel loads and cause greater fire risks (Ruthrof et al., 2016). Following recent record drought and heat conditions across the southwest of Western Australia, a similar die off of trees and shrubs has been reoccurring over a larger area of the South West since February 2024 (Fontaine et al., 2024).

Clearing

Clearing of vegetation causes loss of habitat and is a key threat to biodiversity (Nelder, 2018). Currently, 43% (815,128 ha) of land is cleared in the NJF (EPA, 2023b). The majority of cleared land (85%) has been for rural purposes (e.g. agriculture, private plantation, small land holdings), 11% of land within the conservation estate has been cleared, and 5% has been cleared for mining, predominantly in State Forest (3.5%) (EPA, 2023b).

Vegetation clearing can also have negative effects on fauna through habitat fragmentation and modification, impacting more than 60% of threatened species in Australia (Murphy & van Leeuwen, 2021; Nelder, 2018). Vegetation clearing also changes water regimes by reducing the uptake of water by vegetation, increasing run-off streamflow and water movement through the soil, dissolving naturally occurring salts and increasing salinity (Harper et al., 2019; Shea & Herbert, 1977). Clearing activities can cause soil compaction, decreasing porosity and water infiltration, accelerating erosion and changing plant physiology (Wardell-Johnson et al., 2024). The main drivers for vegetation clearing in the NJF are forestry, agriculture and mining.

Between 2018 and 2022, the Forest Products Commission cleared 225.9 ha of jarrah, 155.8 ha of karri and 11.3 ha of marri from native forest which was below the allowable cut (FPC, 2023). In terms of regeneration for the Jarrah Forest over this period, only 69% (less than the targeted 90%) was revegetated within 30 months primarily due to weather conditions (FPC, 2023). While forestry in the NJF has now ceased, timber may still be harvested for environmental management or development purposes (DJTSI, 2023b). Forestry in the Jarrah Forest can cause changes to fire regimes and potentially the promotion of predation, causing the decline of birds and mammals (Calver & Dell, 1998b). However, there are some documented advantages to timber harvesting. Selective clearing and gap retention timber harvesting have been found to promote regeneration in the Jarrah Forest (McCaw, 2011). Timber harvesting can also increase the availability of coarse woody debris (McCaw, 2011), which can be advantageous for some species.

Although agriculture is a minor industry within the NJF, the removal of vegetation for agriculture can have negative impacts on biodiversity. However, hotter and drier conditions in the South West of Western Australia are likely to reduce agricultural production (Lawrence et al., 2022), potentially mitigating some of this pressure.

Mining commenced in the Jarrah Forest in 1961 with the Government of Western Australia signing the *Alumina Refinery Agreement Act 1961* (Havel, 1989). There are now several types of mining in the NJF, as well as bauxite, mining for other metals (e.g. gold, palladium, platinum, nickel, copper, cobalt) and mineral sands occur. Between 1960 and 2020, 32,130 ha of the NJF has been cleared for bauxite mining (Western Australia, 2022). Rates of clearing in the 1960s were lower at approximately 440 ha per decade, but this has steadily increased over time, with the rate of clearing in the 2010s more than 10,000 ha per decade (Western Australia, 2022). There is currently only a small proportion (~21%) of the NJF that does not have a current mining interest[19]. In preparation for bauxite mining, timber is harvested and other vegetation is cleared, soil is stripped in two layers (topsoil and overburden) and stored, and then blasting and ore removal can commence (Koch, 2007a). While some topsoil is replaced, mining permanently removes the lateritic duricrust and bauxite to mottled zones of the typical NJF soil profile leaving topsoil and pallid clay layers (Campbell et al., 2024). Although mining has been shown to have a negative impact on biodiversity through habitat loss and degradation (Murphy & van Leeuwen, 2021), clearing for mining has been shown to increase streamflow to a peak 4 years after clearing, before returning to previous levels within 11 years (Grigg, 2017).

Fire

Fire from natural causes within the South West of Western Australia typically occur on a 10–15 year cycle (Rundel et al., 2016), however, management regimes currently involve prescribed low to moderate intensity burning on a more frequent basis to reduce the risk of high intensity fires (CPC, 2023). This regime has also been found to maintain litter and promote germination, species diversity and richness, and assist in the cycling of nutrients (Bell & Koch, 1980; CPC, 2023).

Within the last ten years, a significant proportion of the NJF has been burnt (Figure 6a). Several studies have found that fire regimes do not impact tree health (Burrows et al. 2010) or the overall species richness and evenness of macrofungi, vascular flora, ants, beetles, frogs, reptiles and mammals in the NJF (Bell & Koch, 1980; Pekin et al., 2011; Wittkuhn et al. 2011 in Abbott & Williams, 2011). Although others have reported that frequent fires can change species composition by favouring some organisms and reducing the abundance and biomass of others (Pekin et al., 2011; Robinson et al., 2023).

[19] Data source: Mining Tenements (DMIRS-003)

Disease and invasive species

Disease

The current spread of dieback is largely confined to the western extents of the NJF (Figure 6b). Negative consequences of *Phytophthora cinnamomi* have been observed within the NJF, and the Jarrah Forest more broadly, since 1921 (Dell & Malajczuk, 1989; Havel, 1989). Initial reports of 'dieback' were related to smaller patches of forest and more wide spread impacts were not observed until the late 1940s/early 1950s (Dell & Malajczuk, 1989; Havel, 1989). *Phytophthora cinnamomi* was not identified as the cause of dieback until 1964 (Dell & Malajczuk, 1989; Havel, 1989), although, there has been more recent suggestion that other Phytophthora species may also contribute to dieback (Gyeltshen et al., 2021). Initially, infested areas were replanted with exotic dieback resistant species of pines and eucalypts, but these were eventually phased out due to increased fire risk and decreased water yields (Havel, 1989). Rehabilitation was ceased in the west, but continued in the east where the benefits of increased water yield were affected by salinity (Havel, 1989). However, several native species including marri, blackbutt and bullich were found to recolonise dieback infested areas in the west. Currently, 351,096 ha (18%) of the NJF has been mapped as having *P. cinnamomi*[20].

Phytophthora cinnamomi causes not only the death of tree and understorey species but can also significantly reduce the abundance and diversity of macrofungal assemblages (Anderson et al., 2010). *Phytophthora cinnamomi* can persist at heavily infected sites through hosts, infected annuals/herbaceous perennials with or without symptoms that are able to persist and produce new genetic material (Crone et al., 2013). Clearing can assist in the management of *Phytophthora cinnamomi* as it will not persist in the absence of vegetation for 28 months or longer (Crone et al., 2014). Retaining or reinstating tree cover can enable both dieback resilient and dieback susceptible understorey species to persist at *Phytophthora cinnamomi* infested sites (McDougall et al., 2005).

Although more specific to Marri (*Corymbia calophylla*) and red flowering gum (*Corymbia ficifolia*), marri canker disease has the potential to have a severe impact on trees across the southwest of Western Australia (Paap et al., 2012), and it is likely to be well distributed throughout the NJF (see Figure 1 in Paap et al., 2017). Marri canker is caused by the fungal pathogen *Quambalaria coyrecup* which has been introduced to Western Australia from the east coast of Australia (DBCA, 2024a). Marri canker has been found to be associated with fragmented and disturbed habitats and is more prevalent in wetter and cooler areas (Paap et al., 2017; Sapsford et al., 2021). Site disturbance, surrounding non-native vegetation and nearby presence of *Phytophthora* spp. has also been found to increase the incidence of marri canker (Paap et al., 2017; Wardell-Johnson et al., 2024).

Invasive species

Invasive species are the largest driver of native fauna extinction in Australia (Murphy & van Leeuwen, 2021). In particular, the introduction of cats (*Felis catus*) and foxes (*Vulpes vulpes*) to Australia has had a detrimental effect, causing the decline of many terrestrial mammal species, particularly those of smaller size (Woinarski et al., 2015). In the NJF, there are 14 threatened species particularly vulnerable to cats and foxes, including quokka (*Setonix brachyurus*), woylie (*Bettongia penicillata*), chuditch (*Dasyurus geoffroii*) and numbat (*Myrmecobius fasciatus*) (DBCA, 2024b). Other pressures that reduce vegetation cover of forested areas, such as clearing, thinning and fire, can exacerbate the impact of cats and foxes on native fauna, as vegetation can provide hiding places for ground dwelling species (Woinarski et al., 2015).

[20] Source: FMP14 dieback occurrence. Supplied by DBCA under agreement

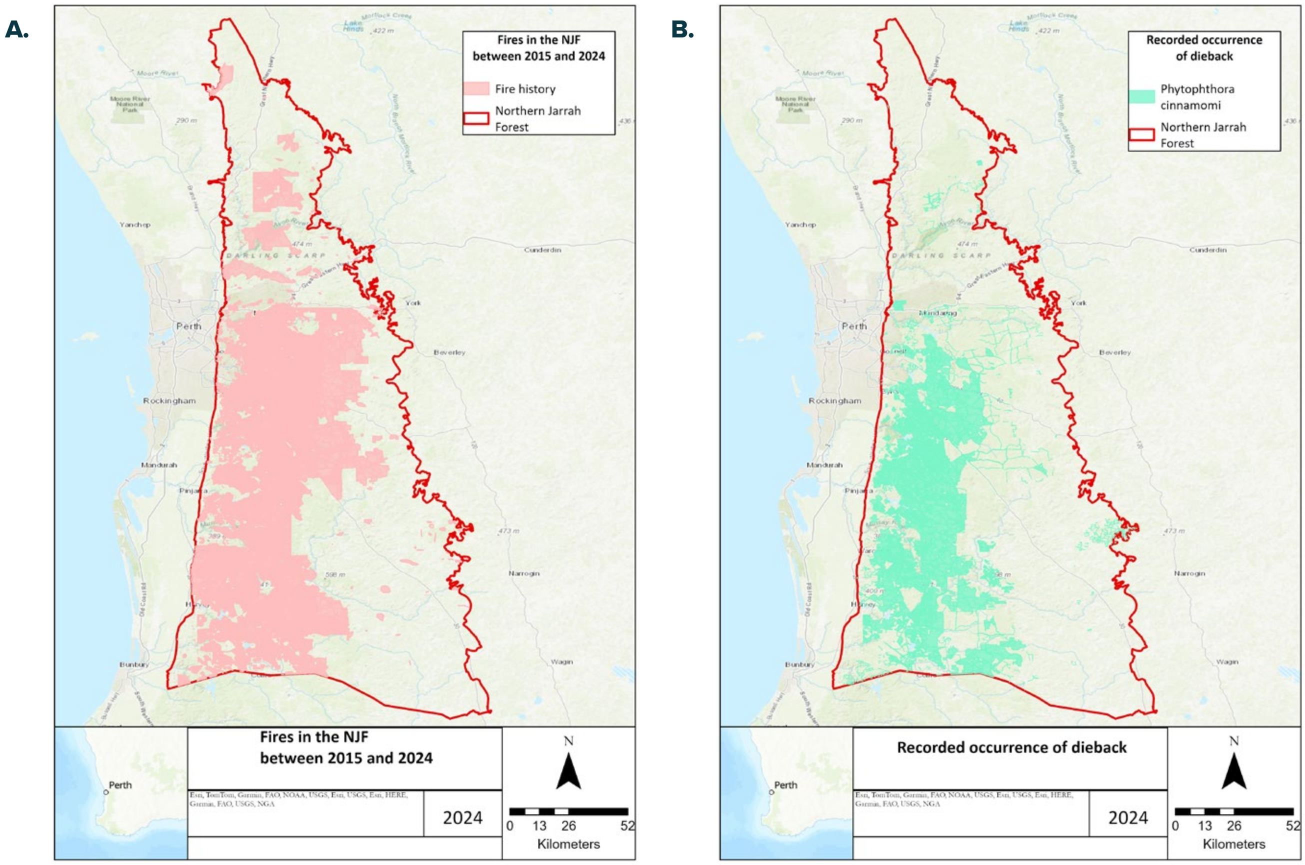

Figure 7. History of disturbance in the NJF: a) Fire history between 2014 and 2023; b) Identified instances of *Phytophthora cinnamomi*

Solutions to key pressures

Protection

The protection of biodiversity and conservation of nature is of high importance to most Australians (Borg et al., 2023). The avoidance of activities that degrade forests alongside the improvement of land management practices may provide some benefit to avoid collapse or transition to an alternative state (Lawrence et al., 2022).

The growth habitat of jarrah trees (i.e. lignotuber) enable the trees to recover quickly from disturbances such as cutting and fire (Shea & Herbert, 1977) and there have been reports of the relatively rapid (within 40 years) return of disturbed areas of jarrah forest to a species composition similar to undisturbed areas (Abbott & Williams, 2011). Natural regeneration of jarrah forest remnants on previously cleared and grazed land has been found to occur within 6 years following removal of pressures such as grazing (Pettit & Froend, 2001). However, disturbance alters the structure of the jarrah forest with large, widely spaced trees, being replaced by smaller denser regrowth (Havel et al., 1989). Avoiding further disturbance on these areas of forest could enable the maturation and transition to a state that is closer to that observed pre-disturbance.

Protection of threatened habitat through a legal mechanism (such as a conservation covenant) can prevent disturbance from reoccurring (Maron & Gordon, 2013). While legal protection of forests can be beneficial, appropriate management of forested areas is required to ensure forest health (Måren & Sharma, 2018).

Restoration

Restoration is defined as the "process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (Gann et al., 2018). The terms revegetation, rehabilitation and restoration are often used interchangeably, even where these activities are required for regulatory purposes, such as offsets. Restoration provides a trajectory towards the recovery of natural values such as representative biodiversity and ecosystem functions and services. Recovery aims to reestablish key ecosystem attributes, such as native species and ecosystem functions, that reflect those in an appropriate native ecosystem (Cross et al., 2018; Gann et al., 2019). Revegetation of degraded areas is a restoration activity that can achieve ecosystem recovery and is a key solution to many of the pressures in the NJF, however there can be a considerable delay before the ecological benefits of revegetation are realised (Cross et al., 2019; Nelder, 2018).

The Society for Ecological Restoration (SER) provides a continuum of actions, including revegetation, rehabilitation and restoration to fully recover native ecosystems (see Gann et al., 2018). While the terms revegetation and rehabilitation are defined by the WA Environmental Offset Guidelines (EPA, 2014), there is no definition of restoration and these definitions differ slightly from those presented by SER and in other literature (e.g. Cross et al., 2019). Additionally, none of these terms are defined by the Commonwealth's Environmental Offset Policy (DSEWPaC, 2012). Given the more detailed explanation provided by SER of all three terms, these definitions have been adopted and provided throughout this document.

Prior to the cessation of native logging in 2024, many areas where timber had been removed were replanted with new stands of timber (FPC, 2023). Developers also revegetated mined areas for the (partial) recovery of biodiversity and ecosystem function. While initial mine site revegetation involved little site preparation and the planting of exotic species including pines, cypress and Eastern Australian eucalypts with little understorey species (Gardner & Bell, 2007; Grant, 2006; Grant & Koch, 2007), since 1988, developers have used native over-story species to restore previously mined areas (Grant & Koch, 2007). The replacement of topsoil to return seed and nutrients to revegetated areas, and the planting of native legumes (e.g. acacias) and other native understorey species have also been subsequently introduced to restore ecosystem biodiversity and function (Gardner & Bell, 2007; Grant & Koch, 2007; South32, 2022a). New techniques have been introduced to improve the success of revegetation too, with preparation of areas to be restored by deep ripping and concentration of seed within topsoil through screening (Gardner & Bell, 2007; Grant & Koch, 2007; South32, 2022a). Planting of recalcitrant species now also occurs (Alcoa, 2024b; Gardner & Bell, 2007; South32, 2022a).

Revegetated areas are monitored for key restoration indicators including vegetation structure, species density, species richness, cover and tree health (Grant, 2006). Where required, management interventions, such as weed control, burning, thinning and replanting, may be implemented to improve the success of the restoration (Grant, 2006; Gardner & Bell, 2007). Developers also undertake restoration in other degraded areas of the NJF as compensation for losses of biodiversity and ecosystem function that cannot be recovered through on-site restoration of developed areas (environmental offsets). Further revegetation in the NJF occurs for conservation purposes (primarily through catchment groups working in the NJF) and for carbon sequestration purposes. However, there is no evidence that this is undertaken within a regional strategic approach. The success of restoration as a solution to key pressures depends on the level of recovery of natural attributes (species, ecosystem functions and ecosystem services) that can be achieved through revegetation and management activities in the context of other interacting processes such as climate change, water availability, seed availability, herbivory and the impacts of previous land management.

Levels of recovery

Levels of recovery following restoration of degraded or cleared areas in the NJF are variable and depend broadly on the return on ecosystem functionality for species in that area, the recolonisation of species that are not reintroduced and the timescales at which restoration are measured. Seedling establishment is strongly related to proximity to undisturbed areas and rainfall patterns across the wet season (White-Toney et al., 2019). Soil carbon and floristic similarity are effective indicators of the similarity of restored areas to undisturbed areas (Koch & Hobbs, 2007), and the available seed stores in topsoil can be used as an indicator of the self-sustainability and resilience of restored areas (Grant et al., 2007a).

To date, there have not been any studies that have found the recovery of all natural values through revegetation. However, some studies have found the full or partial return of some natural values. Campbell et al. (2024) report that while revegetation has been shown to restore natural values in the NJF, revegetation of degraded land has not been as successful, likely due to the permanent removal the lateritic and bauxite layers of soil and subsequent altering of hydrology. Cristescu et al. (2012) found through a meta-analysis of mine site restoration in Australia equal species richness between revegetated areas and undisturbed areas for 29% of studies, but only 10% reported that all species had returned. Similarly, a study undertaken by Koch and Hobbs (2007) found that revegetated mined areas were similar to undisturbed areas in terms of floristic composition and growth but were lacking in biodiversity. Norman et al. (2006) found that revegetated areas after 14 years did not show convergence with undisturbed areas, but instead reflected the initial seed mix, highlighting the need for representative species to be included in the initial revegetation seed mix (Koch, 2007b; Norman et al., 2006). Craig et al. (2018) also found that the vegetation of revegetated mined areas was significantly different to undisturbed areas after 20–22 years and Standish et al. (2021) found that three out of four functional diversity indicators did not reflect undisturbed areas 25 years after revegetation at previously mined sites, with functional evenness and functional dispersion of revegetated areas increasing with age, and functional divergence and functional richness decreasing with age. Species similarity and species richness have also been found to be significantly lower at restored sites. (Standish et al., 2021, Standish et al., 2023).

In the NJF, Alcoa has reported success in the recovery of species richness of vegetation at almost all restored mine sites (Stantec, 2023). However, the compositional similarity of vegetation at these sites to undisturbed areas is unknown, as is the recovery of fauna (Stantec, 2023). South 32 have reported success in the recovery of tree densities following revegetation at previously mined sites (South32, 2022a). While success has been reported, this may not represent restoration; a meta-analysis by Campbell et al. (2024) found that, while ecological recovery of revegetated disturbed sites could be achieved, at previously mined sites this was poor and was not moving to an improved state despite age and adaptive management measures.

Overstorey

The canopy cover of the jarrah forest is open and rarely exceeds 50% (Daws et al., 2021a). Jarrah trees are slow growing, taking approximately 130 years to reach full maturity, and in the NJF are tall (>30 m) and straight, with a width of more than 2 m diameter (Bhandari et al., 2021; Dell & Havel, 1989). *Eucalyptus marginata* (jarrah) has a deep root system (lignotuber) that enables access to stored water during periods of drought, are tolerant of other species and have a low rate of thinning and natural mortality (Bhandari et al., 2021; Daws et al., 2021a), however, the growth of jarrah is impacted by location, rainfall and genetic characteristics including seed provenance (Bhandari et al., 2021). Similarly, *Corymbia callophylla* (marri), also common in the NJF, are a slow growing species that develop lignotubers and grow to approximately 40 m tall (ALA, 2024a; Bhandari, 2021; Hill & Johnson, 1995). *Eucalyptus rudis* and *Eucalyptus wandoo* also form lignotubers, but both are somewhat a smaller species, growing to 20 m and 25 m respectively in the NJF (ALA, 2024b; ALA, 2024c; Brooker and Hopper, 1991; Brooker and Hopper, 1993).

Compared to undisturbed areas, revegetated sites have structural differences in the overstorey, with greater soil-water, nutrient and light availability, causing overstorey trees to have straighter stems and narrower crowns with a greater number of longer, thinner vertically angled branches (Bleby, et al., 2009). Previous reports have suggested that the optimal density of tree planting for revegetation is 1,300 per hectare, which is denser than found in undisturbed areas (Koch & Ward, 2005). However, current mine site revegetation aims to achieve densities of eucalypts in restored areas greater than 300 trees per hectare, with targets of 500–700 (South32, 2022b) and 900 trees per ha (Alcoa, 2015). While planting less dense vegetation may reduce associated costs and the drawbacks of management interventions such as thinning and burning (Craig et al., 2018), planting a lower density of vegetation may reduce genetic flows and increase inbreeding so must be balanced (Millar et al., 2000). Further, gaps in vegetation may promote the growth of weeds and increase the effects of drought, therefore a reduction in tree species should correspond with an increase in planting a diverse and representative understorey species (Daws et al., 2023; Wardell-Johnson et al. 2024).

Understorey

While understorey species are planted alongside overstorey trees, the cost of planting understorey species in high densities can be prohibitively high (Pedrini et al., 2022), and the return of the full complement of understorey species found in undisturbed areas is not always possible (Willyams, 2012). Tuberous, rhizomatous and bulbous plant species are often underrepresented when seeded in revegetated areas due to their difficulty to both propagate and establish (Willyams, 2012). Some underrepresented species can be propagated ex-situ and planted in revegetated areas to ensure greater success (Willyams, 2012), although, it is not always possible to source seed for all species. However, Alcoa has demonstrated some success with this approach by ensuring more than 90% of species richness reflecting undisturbed areas will be achieved, including the planting of 40 species of seedlings propagated ex-situ in 2024 across 450 ha (Alcoa, 2024b). Revegetating areas with moderate stocking rates of large legumes (e.g. acacias) and lower densities of trees may improve the likelihood of these species recruiting from nearby undisturbed areas (Daws et al., 2023). It could also provide benefits by reducing water draw down from newly vegetated areas (Wardell-Johnson et al., 2024). Other species, such as orchids, are reliant on symbiotic mycorrhizal fungi, which, in turn, are dependent on litter (Grant & Koch, 2003). Their reestablishment at revegetated sites can be patchy and is strongly linked to soil health (Collins et al., 2007), therefore, soil health must also be promoted to improve the success of restoration, particularly in areas where soil disturbance has been extensive.

Soil health and microbes

Soil functional ability (measured as community level physiological profiles) has been found to change in response to clearing and revegetation, with these changes persisting for extended periods of time (>22 years) (Banning et al., 2012; Orozco-Aceves et al., 2017). Soil parameters such as total nitrogen and soil pH also show significant changes in the medium period (3.5–8.5 years) following revegetation, however, nutrient accumulation rapidly returns to pre-disturbance levels and ecosystem processes re-establish quickly, with no obvious soil chemical impediment to restoration activities (Koch & Hobbs, 2007; Ward, 2000).

Overstorey cover and litter are closely related to macrofungal assemblages in the Jarrah Forest (Anderson et al., 2010). Mining has been found to significantly alter microbial and fungal communities and, although microbial communities become more similar to undisturbed areas over time, fungal communities may not (Banning et al., 2011). However, several studies have found that ectomycorrhizal fungi may return to similar abundances and diversities at undisturbed areas after 7 years if suitable litter is made available (Gardner & Malajczuk, 1988: Glen et al., 2008; Jasper, 2007). Regardless, while the promotion of soil biodiversity is important to support ecosystem services and plant physiology (Wardell-Johnson et al., 2024), the absence or low abundance of soil symbionts has not been found to prevent revegetation (Jasper, 2007).

Fauna

Revegetation can provide habitat for fauna, and it is expected that mammal, bird, reptile, and ant species will recolonise revegetated areas over time, including those that have been previously disturbed (Craig et al., 2017; Nichols & Nichols, 2003). However, reestablishment of flora does not necessarily lead to the reintroduction of relevant fauna (Cristescu et al., 2012). Natural recruitment of vegetation is highly variable and the restoration of ecosystem functions and services suitable for native animals can take decades or longer to occur (Craig et al., 2012; Nichols & Nichols, 2003). Therefore, management strategies such as provision of coarse woody debris, higher canopy heights and less dense overstorey (to encourage tree growth) that facilitate more rapid revegetation and restoration of ecosystem functions are required (Craig et al., 2012). Prescribed burning and ecological thinning can assist in achieving this, although both may need to be repeated over time until the ecosystem reaches maturity (Craig et al., 2012).

Species habitat and foraging requirements need to be met before fauna will recolonise a revegetated site (Nichols & Grant, 2007). Birds generally recolonise first, but other classes of fauna, such as reptiles can take substantially longer (Craig et al., 2012). Management interventions such as provision of ground shelter and dense, diverse and variable understorey, or the facilitation of higher canopy heights and less dense overstorey (to encourage tree growth) can facilitate recolonisation (Craig et al., 2012; Nichols & Nichols, 2003). Proximity to similar established vegetation and the control of introduced species and exotic predators such as mice, foxes and cats are also important (Brennan et al., 2005; Cristescu et al., 2012; Nichols & Grant, 2007; Nichols & Nichols, 2003). Habitat logs can also facilitate recolonisation by various faunal species including reptiles, mammals and invertebrates for nesting and sheltering, and birds as perching structures (Brennan et al., 2005). They can also create a cooler, moister microclimate to provide protection in particularly warm weather (Brennan et al., 2005). This may become more important to fauna in the NJF with a warming and drying climate.

There are no appropriate species that have been found to indicate the return of fauna to restoration in the NJF (Cristescu et al., 2012; Nichols & Nichols, 2003). Therefore the suite of must be considered to determine if recolonisation of native fauna has been successful.

Birds: The recolonisation of birds into revegetated areas is dependent on vegetation structure (Craig et al., 2015a; Nichols & Grant, 2007). Previous research has found that the vegetation structure of revegetated areas in the NJF is suitable for 95% of bird species within 10 years (Nichols & Grant, 2007). The return of ecosystem function for the Baudin's (*Zanda baudinii*), Carnaby's (*Zanda latirostris*) and forest red-tailed black cockatoo (*Calyptorhynchus banksii naso*) species are of specific focus within the NJF due to their threatened status. Revegetation that includes proteaceous species such as banksia and hakea as well as marri, provides feeding habitat for black cockatoos within eight years (Lee et al., 2010). In some areas, black cockatoos have been found to utilise revegetated areas even earlier, feeding on banksia and hakea within 4 years and jarrah and marri trees within 7 years (Doherty et al., 2016), although foraging activity can be hampered by the presence of predators such as raptors (Lee et al., 2010). Black cockatoos also require available nesting hollows for recolonisation; new nesting hollows take an extended period (>100 years) to develop in revegetated areas (Craig et al., 2021). Additionally, access to water in appropriate proximity to suitable habitat for cockatoos is also a requirement for recolonisation (Craig et al., 2021).

Mammals: The process by which mammals recolonise a restored area varies depending on that species requirements and the rate at which ecological functions relevant to that species return to the revegetated area (Burgar et al., 2015; Craig et al., 2012; Cristescu et al., 2012; Nichols & Grant, 2007). While many ecological functions may return relatively quickly, some functions, such as the provision of older trees as roosting habitat (e.g. for bats), can take an extended period (>40 years) (Burgar et al., 2015). In the NJF, the community composition and species richness of mammals have been found to be comparable after 20 years (Craig et al. 2018). Generalist forging mammals have been found to recolonise first, whereas smaller predators can take longer (Nichols & Nichols, 2003). The presence of structures such as rocks and logs and ensuring that the density of over- and mid-story are similar to undisturbed areas can facilitate the return of some species, for example bat species and marsupials such as the western quoll (Burgar et al., 2017; McGregor et al., 2014). In addition to the provision of habitat and ecological functions, revegetation can benefit mammals through the maintenance of genetic diversity (Mijangos et al., 2017).

Reptiles: Levels of litter and coarse woody debris, tree density, and canopy cover fluctuations impact the recolonisation and persistence of reptiles in revegetated areas (Craig et al. 2018; Koch & Hobbs, 2007; Nichols & Grant, 2007; Nichols & Nichols, 2003; Sinclair et al., 2017; Triska et al., 2016). Management interventions such as thinning and burning of revegetated areas can also increase the abundance and diversity of reptile species (Craig et al., 2010).

Significant differences in reptile species abundance and community composition between revegetated areas and undisturbed areas have been found even 22 years after revegetation (Craig et al. 2018). Some species (e.g. Napoleon's skink (*Egernia napoleonis*)) require coarse woody debris and larger logs to be returned in greater quantities than is pragmatically possible during restoration (Christie et al., 2012; Christie et al., 2013, Craig et al., 2011), with Craig et al. (2014) recommending >5.7 habitat piles ha-1 and ~50 logs ha–1 for the recolonisation of reptiles. Reinstating coarse woody debris in higher densities in corridors could be one way of facilitating habitat needs for species and delivering a pragmatic solution for the return of ecosystem function (Christie et al., 2012; Christie et al., 2013; Craig et al., 2014). However, as coarse woody debris naturally develops slowly, this will need maintenance to ensure that debris persists until ecosystem function has been restored to create adequate debris through natural processes (Craig et al., 2014).

Invertebrates: Invertebrates are expected to recolonise areas to a similar level as undisturbed areas over time, however, several studies on species such as arthropods, ants and other insects have found differences in abundance and species composition between undisturbed and revegetated areas (Koch et al., 2010; Majer et al., 2013; Majer et al., 2007; Nichols & Nichols, 2003). Reintroduction of coarse woody debris and/or sparse application of fine snipped wood during restoration can facilitate the return of invertebrates to restored areas (Koch et al., 2010; Lythe et al., 2017), with Lythe et al. (2017) suggesting that application of snipped wood at 100 t/ha would optimise benefits to invertebrates and without impacting the establishment of vegetation.

Considerations

The recovery of natural values through restoration activities such as revegetation can be impacted by high intensity and/or too frequent fire, climate variability, water availability, herbivory and previous land management practices. The management of revegetated areas through transitional states is also of importance as different transitional states may have different susceptibilities to these pressures (Grant, 2006). For example, high densities of tree and legume species planted during an early transitional state may inhibit the establishment of understorey species and increase the risk of fire (Grant, 2006). Ongoing management of revegetated areas, particularly through transitional states is of prime importance to ensure the restoration of natural values.

Climate change

Climate change has been shown to have a small, but significant, effect on restoration and recovery of natural values, primarily due to changes in rainfall evenness (Standish et al., 2015). Low rainfall can cause recruitment failure in seeded areas (Standish et al., 2018). Given the drying climate and importance of provenance and rainfall zones for NJF species (O'Brien et al. 2007; Koch & Samsa, 2007), seed from the drier eastern NJF is likely to become more important not just for the revegetation of the NJF, but also the southern jarrah forest. However, jarrah from drier zones have a slower growth habit than those from higher rainfall areas, which could result in slower growth of revegetation and restoration of natural values (O'Brien et al., 2007). And a study on marri found evidence that trees from drier provenances may have a higher susceptibility to plant pathogens (Hossain et al., 2022).

Nutrient acquisition and regeneration traits of the vegetation are the primary drivers of response to ecological change in the Jarrah Forest (Pekin et al., 2011). Under a drying climate, a reduction in the density of trees which are higher users of water, to rather focus on understorey species would ensure better water balance and better preserve biodiversity and ecological values of remnant vegetation (Wardell-Johnson et al., 2015).

Water availability

Species composition in the NJF is mostly related to moisture availability (Bell & Koch, 1980; Pekin et al., 2011) and the growth rate of revegetation is strongly linked with mean annual rainfall (O'Brien, 2007; Standish et al., 2015; White-Toney et al., 2019). Young jarrah trees have been shown to develop hydraulic responses relevant to climate and substrate availability; however at revegetated sites, jarrah trees are subjected to modified soils with initially elevated levels of moisture that may hinder tree health when soil moisture decreases (Bleby et al., 2012). Reducing the leaf area index can improve water availability (Croton et al., 2014) and reductions in vegetation have not been found to cause decreases in water quality in Jarrah Forest streams (Shea & Herbert, 1977). Evaporation from understorey, ground flora and bare soil are also important in the consideration of water balance in the Jarrah Forest (Macfarlane et al., 2018).

Seed availability

The availability of native seed is a recognised threat to the achievement of restoration (Goodale, et al., 2023). In particular, shortages of native seed can impact species provenance and the success of restoration (Török et al., 2024). The availability of native seed in Australia is limited, and the quantity and diversity of seed required to revegetate landscapes with the full suite of species to restore degraded areas is deficient (Andres et al., 2024). the effects of climate change on plant reproduction may further reduce both seed availability and viability (Broadhurst et al., 2016). A recent study found that, across Australia, native seed from only 12% of Australian plant species is commercially available (Andres et al., 2024). Understorey species such as grasses and herbs, in particular, have poor availability (Andres et al., 2024). This has implications not only for the restoration of natural values to an area, but also impacts the utilisation of higher proportions of understorey species in revegetation seed mixes to benefit both species recruitment and water use in newly revegetated areas. Expansion of specialised seed production areas, development of large capacity conservation seed banks, further research into improving quality of seed collection, overcoming seed dormancy, germination and storage constraints and sourcing difficult to collect seed may be of benefit to the availability and viability of seed for restoration (Alcoa, 2022; Broadhurst et al., 2016; Goodale et al., 2023; Miller-Sabbioni et al., 2023).

Herbivory

Herbivores, such as kangaroos, have the potential to negatively impact some species included in restoration. The impacts of herbivory can be reduced through fencing and/or the planting sacrificial species to divert herbivory efforts away from rare or vulnerable species (Parsons et al., 2006; Parsons et al., 2007). Plant guards may also provide benefits in terms of protection from herbivory and could provide other advantages by increasing temperature and lowering of light levels around seedlings (Daws & Koch, 2015). Seed harvesting by both vertebrates and invertebrates can also reduce the success of revegetation, although obscuring seed with soil, litter or understorey seedlings can mitigate this (Stoneman & Dell, 1994).

Previous management

Previous management activities may change the function of an area, impacting its ability to be restored. In areas where exotic plants have previously been planted, the soil may contain seed from these species or altered chemistry levels that could make revegetation less successful. In areas where fertiliser has been applied and/or leached from nearby areas, the chemistry of the soil may also be altered (typically elevating phosphorus levels) for an extended period (20+ years), impacting the richness and composition of understorey species (Daws et al., 2019; Daws et al., 2021b; Walters et al., 2021). Fertiliser application is particularly linked to the promotion of weeds and disproportionate benefits for particular species (such as legumes) which may in turn reduce overall biodiversity through competition and smothering from associated leaf litter and debris, altering plant succession pathways (Daws et al., 2022). It can also increase susceptibility to fire (Daws et al., 2022; Norman et al., 2006).

Other mechanisms

Rehabilitation

Similar to restoration, rehabilitation utilises revegetation to return biodiversity and ecosystem function to a landscape, but instead of replicating the biodiversity and integrity of undisturbed areas, rehabilitation aims to return a level of ecosystem functionality and the renewed and ongoing provision of ecosystem goods and services (Cross et al., 2018; Gann et al., 2019). Given that rehabilitation does not actively seek to recover biodiversity and ecosystem integrity, although it may support some of these attributes to passively return, it is unlikely in isolation to provide a strong solution to the loss of biodiversity and the pressures of climate change in the NJF.

Management actions

Disease and Invasive species management

The control of diseases can improve the health of the forest. DPIRD manage biosecurity risk associated with plant disease and invasive species predominantly associated with agriculture (DPIRD, 2024). However, many of these species may also pose risk to native flora and fauna and, therefore, their management also benefits natural values. DPIRD also undertake surveillance to prevent the establishment of new invasive species (DPIRD, 2024).

Invasive species such as the rabbit (*Oryctolagus cuniculus*), fox (*Vulpes vulpes*), cat (*Felis catus*), black rat (*Rattus rattus*), house mouse (*Mus musculus*) and pig (*Sus scrofa*) are found through the NJF and can significant negative impacts on native species, from both predation and competition for habitat (DoE, 2015). The control of cat and fox populations can improve the abundance of small terrestrial mammals (Woinarski et al., 2015). The Western Shield program currently undertaken by DBCA, with additional funding supplied by industry partners (including Alcoa and South32), aims to reduce the populations of cats and foxes to enable the recovery of species threatened by feral animal predation (DBCA, 2024b). The Western Shield program covers a large proportion of the NJF (DBCA, 2024b); however, the program does not extend to private land in the NJF or extensive areas of nearby bioregions[21].

In addition, DBCA has developed a feral cat management strategy to "conserve populations of native species, through effective and adaptive management of feral cats." (DBCA, 2023). The purpose of this strategy is to provide a voluntary framework for the coordinated delivery of feral cat management activities by other organisations including Aboriginal Corporations, landholders and conservation and community organisations (DBCA, 2023).

[21] Western Shield baiting locations can be viewed here: https://www.dbca.wa.gov.au/management/threat-management/invasive-animals/western-shield/western-shield-fox-and-feral-cat-baiting-locations

Forest management

The management of forests can contribute to improved water yield, which is of particular importance for the management of impacts of climate change (Harper et al., 2019). Ecological thinning, used to managed densely planted areas of forest, usually focusses on the removal of weaker and less healthy trees, retaining larger and stronger individuals (Wardell-Johnson et al., 2024). Given that the rate of natural mortality of both jarrah and marri is very low, ecological thinning in the NJF can prevent stagnation and overstocking of forest areas and improve both soil moisture and the balance between catchment water levels and soil salinity (Bhandari, 2021; Wardell-Johnson et al. 2024).

Following the history of logging and clearing for mining, the Jarrah Forest is dominated by areas of regrowth/reforestation trees (high sap wood to basal area), which have a higher water demand than mature forest (Burrows et al., 2011). Heavy thinning (400 stems ha-1 retained) encourages tree growth and reduces leaf area index, creating benefits for increased streamflow and the maintenance of water balance (Bhandari et al., 2021; Burrows et al., 2011; Daws et al., 2021a; Grigg & Grant, 2009; Harper et al., 2019). Thinning also enables the forest to better resemble pre-European forests, improving forest resilience to fires and drought and providing an increase in foraging material and habitat availability (Bhandari, 2021; Bhandari et al., 2021; Burrows et al., 2022; Daws et al., 2021a; Grant et al., 2007b). This may potentially also extend to benefits for the prevention of tree die off from extended periods of drought.

However, the effects of thinning are temporary (Wardell-Johnson et al., 2024) and can cause negative impacts in forested areas through the removal of habitat and disturbance of soil (Bhandari, 2021). There is also some concern that thinning can increase fuel loads, particularly when followed by burning through the promotion of an altered, more flammable understorey composition (Wardell-Johnson et al., 2024). Thinning, through the creation of gaps in vegetation, can increase the establishment of weeds and/or provide additional opportunities for predation by invasive species such as cats and foxes (Wardell-Johnson et al., 2024). Revegetation with understorey species following thinning could provide a solution for these issues.

The changes in soil moisture and increase in soil and bark temperatures caused by thinning can also promote the prevalence of diseases such as *Phytophthora cinnamomi* (Wardell-Johnson et al., 2024). Disturbance of understorey and soil compaction must be minimised whilst thinning is undertaken (Burrows et al., 2022) as must potential changes to soil functional ability (Cookson et al., 2008).

In Western Australia, DBCA undertake ecological thinning in State forests and timber reserves for forest management purposes under the Forest Management Plan, and they plan to thin up to 8,000 ha across Western Australia each year (CPC, 2023). In 2024, ecological thinning of 780 ha of forestry regrowth and 780 ha of ex-mine sites restored in the 1980s is expected to be undertaken on DBCA lands in the NJF (DBCA, 2024c). Trees removed through thinning by DBCA will be made available to FPC for 'salvage, removal and sale' (CPC, 2023).

Fire management

Low intensity, prescribed burning can promote species richness and tree growth, assist in the regeneration of forests and stimulate undergrowth vegetation and tree coppice regeneration (Burrows et al., 2010; Burrows et al., 2019; FPC, 2023; Grigg & Grant, 2009). In forested areas, species richness and diversity are maximised approximately 6 years following a prescribed burn, when both obligate reseeder species (favoured by fire) and resprouting species (favouring lack of burning) are present (Bell & Koch, 1980; Vlahos and Bell, 1986). While burning causes some initial species composition changes to the soil seedbank, this is temporary (Koch et al., 2009). Although burning decreases the risk of high intensity fires by reducing flammable materials such as understorey, coarse woody debris and logpiles, it may have a negative effect on fauna species including small mammals and reptiles, as these materials provide refuges (Calver & Dell, 1998b; Grigg & Steele, 2011). Providing additional habitat structures, such as larger diameter logs can mitigate against this (Grigg and Steele, 2011).

The seasonality of burning can be important. Low intensity burns in spring, when wood is still wet from winter rains, can also support the retention of coarse woody debris (McCaw, 2011). Although, spring burning such as this may have negative impacts on fauna such as birds, that breed in spring (Calver & Dell, 1998b). Spring burning can also promote seeding over summer and autumn causing a higher incidence of seed decay and predation, thus decreasing available seed for germination in winter (Ryan et al., 2023).

The timing of burning following prior fires, revegetation or thinning is similarly an important consideration. Fuel loads in previously burnt and/or revegetated areas change over time (Smith et al., 2004). High fire frequency and out of season fires have been reported as causing the loss of structure and canopy succession through the loss of mature trees, reducing understorey diversity and depleting the seed bank, which can have very large consequences for faunal species, with listed species particularly vulnerable (Campbell et al., 2023).

Restored Jarrah Forest of less than 5 years of age can act as an efficient fire break (Smith et al., 2004). Smith et al. (2004) reported that low intensity prescribed burning should occur in revegetated areas greater than 8 years to reduce fuel loads and facilitate succession. While Morley et al. (2004) recommended that revegetated areas should not be burnt for 12–15 years and this burning should be low intensity and conducted in spring to enable the best opportunity for rapid recovery of nutrient levels. Similarly, Grant and Koch (2003) reported that burning of revegetated areas after more than 10 years increases the density of orchids. Grigg et al. (2010) reported that burning should only occur 1–2 years following thinning; otherwise it can increase fire risk by creating a dense well-aerated and elevated fuel layer.

Credits and markets

Environmental offsets, nature credits and carbon credits are all nature-based market mechanisms that could fund protection, restoration and management activities as solutions to key pressures in the NJF. Environmental offsets are currently the most broadly utilised for this purpose. However, offsets have been questioned about their ability to provide adequate compensation for the environmental impacts of development and the potential to cause socioecomonic inequalities (Abdo et al., 2021; Bidaud et al., 2018; Fallding, 2014; May et al., 2017; Tupala et al., 2022; zu Ermgassen et al., 2019). While this can occur, if offsets are implemented strategically within bioregional plans they not only can provide adequate compensation for the environmental impacts of development, but can also provide funding and resources for contribution to regional conservation goals by improving ecological connectivity and resourcing conservation activities and ecological management across a region (Abdo et al., 2019; Abdo, 2023; Kiesecker et al, 2009; Rosa et al., 2022; Takacs, 2018). Both DCCEEW and DWER are committed to undertaking regional planning, however, a timeframe for the development of regional plans for the jarrah forest are yet to be identified.

While offsets are known to be undertaken in the NJF, it is unclear if other credit mechanisms (e.g. carbon, nature) have been employed in this region. Crediting mechanisms can be either voluntary through private or government organisations or, in the case of environmental offsets, may be required as part of an environmental approval. The Australian government has a detailed carbon crediting scheme available and is currently investigating methodologies for nature credits under the recently announced Nature Repair Market (DCCEEW, 2024e). When available, the Nature Repair Market is expected to issue tradeable biodiversity certificates which may overlap the NJF. Aboriginal people and corporations, conservation groups and farmers are all identified as entities that may generate biodiversity certificates (DCCEEW, 2024e). In addition, there are many other organisations globally that have developed and/or certify both carbon and nature credits. Whilst this is still untested, these credits may provide another avenue for the generation of funding and resourcing for conservation in the NJF.

Opportunities

The review of literature presented above yielded several opportunities that, if addressed, could reduce pressures and provide additional knowledge for better ecological outcomes and improved management activities in the NJF. However, the implementation of conservation measures can be prohibitively expensive. For example, a report issued by the Wentworth Group of Concerned Scientists estimates that an investment of $7 billion per year for 30 years of conservation actions, plus an ongoing budget of $250 million for maintenance outcomes, is required to restore all of Australia's degraded terrestrial habitats to 30% of their original extent (WGCS, 2024). Environmental offsets have been shown to provide funding and incentives for environmental restoration, the improvement of ecosystem connectivity and a significant contribution to regional conservation goals (Fallding, 2014; Kiesecker et al., 2009; Rosa et al., 2022; Takacs, 2018).

Of relevance to environmental offsets, which may contribute to this funding, is the revegetation and maintenance of salt affected areas and eroded gullies; the conservation, restoration and reestablishment of connectivity along rivers, wetlands and floodplains; the restoration of degraded non-prime agricultural land; the restoration and removal of threats for threatened species (WGCS, 2024).

Additionally other crediting systems could provide incentives for further activities to reduce pressures within the NJF. Revegetation of cleared and/or degraded areas can provide benefits in terms of carbon sequestration and other nature benefits that may be valued as saleable credits (DCCEEW, 2024c; DCCEEW, 2024f). For example, avoidance of vegetation removal can generate carbon credits either through forest management (FM) credits or Kyoto-Australian carbon credit units (Kyoto ACCUs); this has already been shown to be significant for forestry (Macintosh, 2012). Similarly, when available, there is potential for ecological improvement and management activities to provide nature credits.

Ecological management for improved water yield

Thinning of revegetated areas can create benefits for tree growth, enabling a lesser time to maturity of the forest and potential for harvesting, and reduce water needs by the forest thus increasing streamflow (Grigg & Grant, 2009). In 1977, 80% of Perth's water came from the Jarrah Forest catchments and it was identified that demand for water was approaching its maximum yield (Shea & Herbert, 1977). Since that time, population and water use has increased and rainfall has decreased. Ground water, stream water and soil-water storages across the NJF have all declined and are on a trajectory whereby further decline is expected (Croton et al., 2014). Without active management such as thinning, the NJF will transition to a new water balance where previously permanent streams become ephemeral, impacting species diversity (Harper et al., 2019). For example, vulnerable forest red-tailed black-cockatoos require proximity (<1 km) of water to nesting hollows; therefore provision of water sources in key nesting areas for black cockatoos will be of importance to the species particularly in a drying climate (Craig et al., 2021).

Clearing activities for mining and agriculture and ecological thinning of forested areas has a positive impact on the water yield of the NJF (Bari & Ruprecht, 2003). However, revegetation and the reinstatement of forest cover, despite obvious benefits in terms of natural values, has been found to reduce water yields to previous levels within 12 years (Bari & Ruprecht, 2003). Younger trees found within revegetated areas have a higher proportion of biomass in leaves and use almost twice as much water on average than mature forest (Bleby, et al., 2009; Macfarlane et al., 2010). Revegetated areas have initially higher levels of moisture that these younger trees become accustomed to and therefore may have a lower resilience to dryer conditions that are expected under an altered climate (Bleby et al., 2012; O'Brien et al., 2007). Management activities such as thinning and/or exposing younger trees to dryer conditions could maintain more similar attributes to mature forest and ensure the resilience of revegetated areas in the face of a drying climate (Macfarlane et al., 2010). Additionally, given that seed provenance can impact overstorey growth (Bhandari et al., 2021), utilising seed from the dryer north eastern area of the NJF could further reduce the hydraulic requirements of the revegetation and mitigate against a further drying climate.

In cleared or thinned areas, revegetation focussing on abundance and diversity of understorey species would have benefits to both water balances and biodiversity (Wardell-Johnson et al., 2015; Wardell-Johnson et al., 2024). Whilst this would negate the ability to restore all ecosystem values to the revegetated area, in the context of the broader bioregion it may provide a strategic benefit, particularly in the predicted warming and drying climate scenario (Wardell-Johnson et al., 2015; Wardell-Johnson et al., 2024). However, given that the availability of seed for understorey species is particularly lacking (Andres et al., 2024), care would need to be taken to ensure that biodiversity, genetic diversity, ecosystem functions and ecosystem services were maintained across the bioregion.

In areas revegetated by developers, thinning, improvement/maintenance of understorey and management of water balances should be incorporated into ongoing management activities to ensure the success of revegetation and the trajectory towards restoration/rehabilitation. However, management of already forested areas and those revegetated following forestry is within the remit of governments (Burrows et al., 2022). As management of water balances are recognised as a priority for the health and resilience of the NJF, valuation of water balances through nature credits and/or environmental offsets could provide incentives for improve forest management in the NJF (Harper et al., 2019).

Protection of existing forested areas

The protection and maintenance of existing areas of native vegetation is more economical, efficient and lower risk than the restoration of degraded areas. In line with the Kunming-Montreal Global Biodiversity Framework, Australia has committed to expand the existing reserve network and protect and conserve 30% of all terrestrial areas by 2030 (CBD, 2024b, DCCEEW, 2024g). Therefore, additional protected areas have been proposed to ensure that all terrestrial habitats are adequately represented (CPC, 2023; Martin et al., 2022). New areas for protection that will strategically contribute to these goals have been suggested by both DBCA's Forest Management Plan (CPC, 2023) and by conservation groups (i.e. Martin et al., 2022).

To ensure the expansion of conservation areas, land must be purchased or compensation provided to landholders, and ongoing management of these areas will require additional funding. While the Commonwealth has committed some funding for this purpose (DCCEEW, 2024g), this is unlikely to be sufficient to achieve this goal. However, land acquisition could be achieved strategically through environmental offsets.

Restoration of previously rehabilitated areas

Many areas mined and revegetated prior to 1988 were revegetated with non-native species. In addition several of these non-native species were also planted within forested areas of the jarrah forest during this period (Wardell-Johnson et al., 2024). Many of these species are proliferating with the changes in climate being experienced by the jarrah forest and therefore their resilience and distribution is likely to increase (Wardell-Johnson et al., 2024). Further, although many previous revegetation efforts have aimed to achieve restoration, only a subset of ecosystem functionality delivered better reflecting rehabilitation (Campbell et al., 2024). Replacing these areas with species native to the NJF could provide restoration of natural values (Burrows et al., 2022), that could be valued as nature credits/environmental offsets.

Native plants and seeds are also a significant food source for many species of native fauna; therefore, the return of these native species can also benefit recolonisation of native fauna species (Nichols & Grant, 2007; Stoneman & Dell, 1994). Burning of older rehabilitated sites that include eastern Australian species can also help to lower densities of these species and then stimulate the reestablishment of native flora and recolonisation of native fauna. Revegetated areas reaccumulate fuel loads rapidly in the first year following fire, but fuel loads stabilise after this point (Grant, 2003). Fire removes dead material and stimulates undergrowth assisting restoration (Grant, 2003). While, fire also stimulates weed growth and slows tree growth, the effects of this are negligible after two years (Grant, 2003). Seeding and/or planting native seedlings following burning could further facilitate restoration.

Disease and invasive species management

Clearing vegetation can eliminate dieback as spores do not persist in the soil, but the site needs to be vegetation free for 28 months (Crone et al., 2014; Gyeltshen et al., 2020). Where vegetation clearing is necessary, there is potential for this clearing to be targeted towards areas infested with dieback to contribute to the eradication of this disease. Revegetation could then follow after 28 months to ensure that dieback has been eliminated. Alternatively, revegetation could commence earlier, reducing the lag time in the restoration of ecosystem function, but be staged to consider the response of plants to *Phytophthora cinnamomi* infection. Revegetation with species resistant to infection in the emergence phase could be commenced as soon as possible following clearing. Infill planting with species that are resistant during the early survival phase of growth could follow later, but still within the period of potential infection. Finally, infill planting with the remaining complement of appropriate species for that area (including susceptible species and potential host species) could commence when the risk of dieback infection is less (see Table 3).

While invasive species are the greatest threat to Australian fauna, management of invasive species is very costly (Murphy & van Leeuwen, 2018). Feral cats and foxes, in particular, have had a large impact on Australian wildlife, contributing to many extinctions (ISC, 2024a; Murphy & van Leeuwen, 2018). As invasive species are spread across almost the whole of Australia (ISC, 2024b), broadscale approaches are necessary to combat this pressure. In Australia, all three levels of government (local, state/territory and Commonwealth) have a responsibility to manage invasive species (DEH, 2004). Plant diseases and invasive species are managed in Western Australia by both DBCA and the Department of Primary Industries and Regional Development (DPIRD) through their responsibilities to biodiversity conservation and the management of biosecurity respectively (DBCA, 2024b; DPIRD, 2024). However, landholders, local governments and conservation groups also may undertake more locally focussed invasive species and disease management programs (DEH, 2004).

Table 2. : List of species resistant to *Phytophthora cinnamomi* infection. Summary of results from Harshani et al. (2023)

Emergence phase only	Early survival phase only	Both emergence and early survival phases
Calothamnus sanguineus	*Acacia neurophylla*	*Acacia acuminata*
Eucalyptus macrocarpa	*Acacia pycantha*	*Calothamnus gilesii*
Kunzea pulchella	*Acacia saligna*	*Calothamnus hirsutus*
Kunzea recurva	*Astartea scoparia*	*Hakea laurina*
Rhagodia preisii	*Banksia repens*	*Hakea petiolaris*
	Callistemon phoeniceus	*Hakea trifurcate*
	Calothamnus quadrifidus	*Melaleuca adnata*
	Hakea ruscifolia	*Melaleuca pressiana*
	Templetonia retusa	*Melaleuca seriata*

= species identified with moderate or high resistance in the longer term

= host species

The management of diseases and invasive species can be complex, and eradication of invasive species in the NJF is unlikely to be achievable (DEH, 2004). However, valuation of these approaches as contributions to nature credits or environmental offsets could be considered to expand and further fund management practices for the control of disease and invasive species.

Gaps in knowledge

Very little of original condition forest remains in the NJF due to previous clearing for timber and development and changes to burning regimes (Daws et al., 2021a; DBCA, 2019; Havel et al. 1989). Further, the natural disturbance patterns (fire, insects, disease, windstorms) of the NJF are not well understood (Stoneman, 2007). If revegetation and ecosystem management are undertaken without consideration to the original structure and function of the NJF in the context of natural disturbance patterns and the changing climate, then natural values may be lost. Further research into natural disturbance patterns and climate resilient restoration of the NJF would be of advantage to ensure that biodiversity is retained, and appropriate ecosystem functions and services can persist.

The level of recovery of disturbed areas in the NJF in terms of vegetation composition and fauna recolonisation is not well resolved. Further, as knowledge of the original structure and function of the NJF in the context of natural disturbance patterns is unknown, then the measurement of current restoration activities may not ensure the recovery of natural values. Further research into the recovery of flora and fauna through restoration in the context of climate resilience and natural disturbance patterns could ensure that revegetation and environmental offsets recover biodiversity and ecosystem functions and services.

Indicator species have not been identified for the NJF and, generally, a biodiversity approach to monitoring is more appropriate (Abbott & Williams, 2011). However, the assessment of ecological services and functions in the NJF and appropriate indicator species that might represent these functions and services would provide benefits for the monitoring and assessment of both the health of undisturbed areas and the ongoing success of revegetated/ managed areas.

There is a paucity of knowledge related to both invertebrates and reptiles in the NJF. Knowledge of the diversity of invertebrates that inhabit the NJF is lacking (Grant & Koch, 2007). Similarly, understanding of the interactions between reptile species, resource use by reptiles and the influence of edge effects during revegetation and recolonisation is unclear (Craig et al., 2015b).

The expansion of conservation areas within the NJF is a recognised priority, however there is no environmental protection category that can prevent disturbance activities such as mining (CPC, 2023; Martin et al., 2022). Conversely, legal mechanisms for the protection of conservation areas, such as conservation covenants, exclude income generating activities. Whilst this is for the protection of a conservation area, it can reduce the incentive for landholders to participate in conservation. There are several income generating activities that are not incompatible with conservation including ecotourism, beekeeping, sustainable seed collecting etc. Development of appropriate legal mechanisms that will protect and conserve high quality vegetation whilst both enabling compatible income generating activities and excluding non-compatible disturbance activities but would be if benefit to the NJF. Alternatively, development of an industry-wide commitment to avoid conservation areas would also be of benefit to the prevention of disturbance activities in conservation areas.

Although the Forest Management Plan provides a plan of management for DBCA lands in the NJF (CPC, 2023), and the Beyond 2024 report provides a plan for expanded conservation areas in the NJF (Martin et al., 2022), to date, a strategic plan for the whole of the NJF in recognition of cultural and socioeconomic priorities has not been developed. Strategic plans developed with reference to environmental, cultural and socioeconomic priorities can optimise conservation outcomes, such as implementation of landscape scale corridors for key species, and reduce the risk of negative impacts such as the spread of disease, fire and susceptibility to climate change that can compromise natural values including biodiversity and ecosystem function and health (Abdo et al., 2019; Kormos et al., 2015). Strategic plans can also improve the efficiency and effectiveness of offsets by reducing costs and risk, and support market mechanisms such as those required for environmental offsets (Abdo et al., 2019).

Collaborative approaches

Collaborative approaches to the delivery of protection, restoration and management activities can create efficiencies by lowering costs, preventing overlap of effort and improve effectiveness (Guillet & Semal, 2018; Lodhia et al., 2018; Maron & Louis, 2018). Collaborative approaches are of particular benefit to the incorporation of cultural and socioeconomic aspects, thus contributing to the goals of sustainable development. Transparent collaborative approaches can also contribute to continuity and longevity of protection, restoration and management activities, particularly when provided in conjunction with ongoing funding, such as through a conservation fund (Abdo, 2023; Bath et al., 2020; Meyers, 2020).

Approximately 748,510 ha[22] (40%) of the NJF has been identified as potentially arable land. Agricultural practices such as cropping have some benefits in terms of carbon sequestration. Sustainable agricultural practices such as cover cropping and crop rotation, precision irrigation, and diverse cropping and agroforestry can provide significant environmental benefits (UCS, 2022; UNEP, 2021). However, many of these activities are more costly to implement (UNEP, 2021). Supporting activities such as agroforestry represents an opportunity to contribute to sustainable landscape management (Plieninger et al., 2020) and deliver nature benefits (including credits and/or offsets) without incurring negative socioeconomic impacts.

Aboriginal people have a strong connection to land and an intimate knowledge of environmental management and plant species. Their knowledge and connection to country has been highlighted as necessary to achieve environmental goals (Cresswell et al., 2021). To date, this knowledge and experience has not been captured for the NJF (Gnaala Karla Booja Aboriginal Corporation pers. comm.). Building relationships and working with Aboriginal people to integrate cultural knowledge for the improvement of sustainability and repair of damaged ecosystems is imperative (Cresswell et al., 2021). Incorporating cultural knowledge of plants into revegetation and ecosystem management and ensuring that useful plants (i.e. medicinal plants) are introduced into revegetation is of both environmental and socioeconomic benefit (Gnaala Karla Booja Aboriginal Corporation pers. comm.).

Following the South West Native Title Settlement (SWALSC, 2022), Aboriginal people with connection to the NJF may have land that requires cultural and ecological improvement. Working with Aboriginal people to improve their land and surrounding areas of the NJF represents an opportunity to achieve environmental offsets and/or other crediting mechanisms. Collaborations with Aboriginal people for cooperative and joint management of conservation areas is aligned with the EPA's Public Advice on offsets (EPA, 2024), as well as DBCA's Forest Management Plan (CPC, 2023), the WA Department of Premier and Cabinets Closing the Gap (DPC, 2024), and the Aboriginal Empowerment Strategy (DPC, 2021).

Collaborative approaches with other landholders may also be available for protection, restoration and management activities such as government-owned freehold land outside of the conservation estate and land owned by conservation groups. Working with stakeholders across all sectors to recognise environmental, cultural and socioeconomic value can also assist in the identification of collaborative approaches to further protection, restoration and management activities.

[22] Data source: Potentially Arable Land (DPIRD-026)

Conclusion

The NJF is of environmental, cultural and socioeconomic significance. However, it has several competing uses as primary source of water for the Perth region, large areas of arable land, key development areas for extractive resources, and significant cultural, recreational and social values associated with high biodiversity and traditional use.

In addition to the impacts of these uses, the NJF is also under pressure from the impacts of climate change, fire regimes, diseases and invasive species. The use of environmental offsets, within a strategic regional plan, can reduce these pressures and also fill gaps in ecological knowledge. However, to ensure that offsets are strategic, consideration of the environmental, cultural and socioeconomic priorities for the NJF must be factored into offset planning and design. The use of mapping and data analysis provides an opportunity to identify areas that could be prioritised for protection, restoration, and management activities including through environmental offsets and other crediting mechanisms.

Given that most of the NJF is currently designated as either potentially arable land (40%) or is DBCA land within the conservation estate (45%), very little area remains available to provide compensation for the significant residual environmental impacts of development. Novel and collaborative approaches to offsetting such as ecological management for improved water yields, legal protection of priority conservation areas, restoration, disease and invasive species management, addressing knowledge gaps, and adopting collaborative approaches with agriculturalists, Aboriginal people and local communities could provide strategic environmental solutions to key pressures, and will be required for ongoing development activities in the NJF.

Data sources

Data layer name	Date of last update	Source
IBRA7_regions	6/11/2023	https://hub.arcgis.com/datasets/fd39705085b348e88810eb935a663704/explore
IBRA Subregion Australia Version 7.0 - PED	13/04/2022	https://data.gov.au/data/dataset/e5a6d60a-009c-4fc3-b27d-67ed108b38ba
Southern and South-Western Flatlands data layers	2015	https://terranova.org.au/repository/southern-and-southwestern-flatlands-nrm-collection/southern-and-south-western-flatlands-data-layers
DBCA - Legislated Lands and Waters (DBCA-011)	19/10/2023	https://catalogue.data.wa.gov.au/dataset/dbca-legislated-lands-and-waters
Forest Management Plan (FMP) 2024 – 2033 (DBCA-078)	16/01/2024	https://catalogue.data.wa.gov.au/sl/dataset/forest-management-plan-fmp-2024-2033-dbca-078
Threatened Ecological Communities (DBCA-038)	8/12/2022	https://catalogue.data.wa.gov.au/dataset/threatened-ecological-communities
Aboriginal Cultural Heritage - Register (DPLH-099)	6/05/2024	https://catalogue.data.wa.gov.au/dataset/aboriginal-cultural-heritage-register
Groundwater Salinity Statewide (DWER-026)	19/06/2018	https://catalogue.data.wa.gov.au/dataset/groundwater-salinity-statewide
RIWI Act, Surface Water Areas and Irrigation Districts (DWER-037)	20/06/2018	https://catalogue.data.wa.gov.au/dataset/riwi-act-surface-water-areas-and-irrigation-districts
RIWI Act, Groundwater Areas (DWER-034)	20/06/2018	https://catalogue.data.wa.gov.au/dataset/riwi-act-groundwater-areas
Public Drinking Water Source Areas (DWER-033)	30/04/2024	https://catalogue.data.wa.gov.au/dataset/public-drinking-water-source-areas
Mining Tenements (DMIRS-003)	16/05/2024	https://catalogue.data.wa.gov.au/dataset/mining-tenements-dmirs-003
DBCA Fire History (DBCA-060)	01/07/2023	https://catalogue.data.wa.gov.au/dataset/dbca-fire-history
FMP14 dieback occurrence	23/05/2024	Supplied by DBCA and used under agreement
Potentially Arable Land (DPIRD-026)	23/05/2018	https://catalogue.data.wa.gov.au/dataset/potentially-arable-land-dpird-026
Threatened Ecological Communities (DBCA-038)	08/12/2022	https://catalogue.data.wa.gov.au/dataset/threatened-ecological-communities

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Appendix 1

Protected matters search of the Northern Jarrah Forest subregion[23]

Threatened ecological communities identified within the Northern Jarrah Forest

Community name	Threatened category	Text
Shrublands and Woodlands of the eastern Swan Coastal Plain	Endangered	Community known to occur within area
Corymbia calophylla – Kingia australis woodlands on heavy soils of the Swan Coastal Plain	Endangered	Community known to occur within area
Tuart (*Eucalyptus gomphocephala*) Woodlands and Forests of the Swan Coastal Plain ecological community	Critically endangered	Community may occur within area
Eucalypt Woodlands of the Western Australian Wheatbelt	Critically endangered	Community likely to occur within area
Empodisma peatlands of southwestern Australia	Endangered	Community may occur within area
Corymbia calophylla – Xanthorrhoea preissii woodlands and shrublands of the Swan Coastal Plain	Endangered	Community known to occur within area
Banksia Woodlands of the Swan Coastal Plain ecological community	Endangered	Community likely to occur within area
Clay Pans of the Swan Coastal Plain	Critically endangered	Community likely to occur within area

Threatened flora identified within the Northern Jarrah Forest

Common name	Scientific name	Threatened category	Presence text
null	*Grevillea sp. Gillingarra (R.J. Cranfield 4087)*	Critically endangered	Species or species habitat known to occur within area
null	*Leucopogon sp. Flynn (F. Hort, J. Hort & A. Lowrie 859)*	Critically endangered	Species or species habitat known to occur within area
null	*Synaphea sp. Serpentine (G.R. Brand 103)*	Critically endangered	Species or species habitat likely to occur within area
Broad-fruited Haloragis	*Haloragis platycarpa*	Critically endangered	Species or species habitat likely to occur within area
Dark-bract Banksia	*Banksia fuscobractea*	Critically endangered	Species or species habitat may occur within area
Muchea Bell	*Darwinia foetida*	Critically endangered	Species or species habitat may occur within area
Branched Hemigenia	*Hemigenia ramosissima*	Critically endangered	Species or species habitat known to occur within area

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[23] The protected matters search was conducted on the Northern Jarrah Forest IBRA subregion (no buffer) on 7 May 2024

Threatened flora identified within the Northern Jarrah Forest *(continued)*

Common name	Scientific name	Threatened category	Presence text
Spider Net Grevillea	*Grevillea thelemanniana*	Critically endangered	Species or species habitat may occur within area
null	*Stylidium semaphorum*	Critically endangered	Species or species habitat known to occur within area
Selena's Synaphea	*Synaphea sp. Fairbridge Farm (D. Papenfus 696)*	Critically endangered	Species or species habitat known to occur within area
null	*Conospermum galeatum*	Critically endangered	Species or species habitat known to occur within area
Native Foxglove	*Dasymalla axillaris*	Critically endangered	Species or species habitat may occur within area
Orange Dryandra	*Banksia aurantia*	Critically endangered	Species or species habitat known to occur within area
Velvety Spiral Pod Wattle	*Acacia cochlocarpa subsp. velutinosa*	Critically endangered	Species or species habitat may occur within area
Midlands Gum, Jingymia Gum	*Eucalyptus pruiniramis*	Endangered	Species or species habitat known to occur within area
Saltmat	*Roycea pycnophylloides*	Endangered	Species or species habitat likely to occur within area
null	*Acacia chapmanii subsp. australis*	Endangered	Species or species habitat known to occur within area
Slender Andersonia	*Andersonia gracilis*	Endangered	Species or species habitat likely to occur within area
Summer Honeypot	*Banksia mimica*	Endangered	Species or species habitat known to occur within area
Asymmetric Triggerplant	*Stylidium asymmetricum*	Endangered	Species or species habitat known to occur within area
King Spider-orchid, Grand Spider-orchid, Rusty Spider-orchid	*Caladenia huegelii*	Endangered	Species or species habitat known to occur within area
Purdie's Donkey-orchid	*Diuris purdiei*	Endangered	Species or species habitat known to occur within area
Nangetty Grass	*Glyceria drummondii*	Endangered	Species or species habitat known to occur within area
Shy Featherflower	*Verticordia fimbrilepis subsp. fimbrilepis*	Endangered	Species or species habitat known to occur within area
null	*Synaphea sp. Pinjarra Plain (A.S. George 17182)*	Endangered	Species or species habitat known to occur within area
Cadda Road Mallee, Cadda Mallee	*Eucalyptus x balanites*	Endangered	Species or species habitat known to occur within area
Star Sun-orchid	*Thelymitra stellata*	Endangered	Species or species habitat known to occur within area
Wongan Melaleuca	*Melaleuca sciotostyla*	Endangered	Species or species habitat known to occur within area
Hook-point Poison	*Gastrolobium hamulosum*	Endangered	Species or species habitat likely to occur within area
Red Snakebush	*Hemiandra gardneri*	Endangered	Species or species habitat may occur within area
Scarlet Leschenaultia	*Lechenaultia laricina*	Endangered	Species or species habitat likely to occur within area

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Threatened flora identified within the Northern Jarrah Forest *(continued)*

Common name	Scientific name	Threatened category	Presence text
Scarp Darwinia	*Darwinia apiculata*	Endangered	Species or species habitat known to occur within area
Vassal's Wattle	*Acacia vassalii*	Endangered	Species or species habitat likely to occur within area
Cossack Spider-orchid	*Caladenia dorrienii*	Endangered	Species or species habitat likely to occur within area
Glossy-leafed Hammer Orchid, Glossy-leaved Hammer Orchid, Warty Hammer Orchid	*Drakaea elastica*	Endangered	Species or species habitat known to occur within area
Tufted Plumed Featherflower	*Verticordia plumosa var. ananeotes*	Endangered	Species or species habitat may occur within area
Green Hill Thomasia	*Thomasia sp. Green Hill (S. Paust 1322)*	Endangered	Species or species habitat likely to occur within area
Dwellingup Synaphea	*Synaphea stenoloba*	Endangered	Species or species habitat known to occur within area
Spiral-fruited Wattle	*Acacia cochlocarpa subsp. cochlocarpa*	Endangered	Species or species habitat may occur within area
Wongan Cactus	*Daviesia euphorbioides*	Endangered	Species or species habitat may occur within area
Silver Mallet	*Eucalyptus recta*	Endangered	Species or species habitat may occur within area
One-headed Smokebush	*Conospermum densiflorum subsp. unicephalatum*	Endangered	Species or species habitat known to occur within area
Sprawling Spiky Adenanthos	*Adenanthos pungens subsp. effusus*	Endangered	Species or species habitat likely to occur within area
Western Wheatbelt Wattle	*Acacia brachypoda*	Endangered	Species or species habitat known to occur within area
Western Prickly Honeysuckle	*Lambertia echinata subsp. occidentalis*	Endangered	Species or species habitat may occur within area
Wongan Featherflower	*Verticordia staminosa subsp. staminosa*	Endangered	Species or species habitat may occur within area
Scaly Butt Mallee, Scaly-butt Mallee	*Eucalyptus leprophloia*	Endangered	Species or species habitat may occur within area
a shrub	*Boronia capitata subsp. capitata*	Endangered	Species or species habitat likely to occur within area
Large-fruited Tammin Wattle	*Acacia ataxiphylla subsp. magna*	Endangered	Species or species habitat may occur within area
Keighery's Macarthuria	*Macarthuria keigheryi*	Endangered	Species or species habitat may occur within area
Cinnamon Sun Orchid	*Thelymitra dedmaniarum*	Endangered	Species or species habitat known to occur within area
a shrub	*Grevillea corrugata*	Endangered	Species or species habitat known to occur within area
Rough Emu Bush	*Eremophila scaberula*	Endangered	Species or species habitat known to occur within area
null	*Diplolaena andrewsii*	Endangered	Species or species habitat known to occur within area

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Threatened flora identified within the Northern Jarrah Forest *(continued)*

Common name	Scientific name	Threatened category	Presence text
null	*Goodenia arthrotricha*	Endangered	Species or species habitat known to occur within area
Curved-leaf Grevillea	*Grevillea curviloba subsp. curviloba*	Endangered	Species or species habitat known to occur within area
Diels' Daviesia	*Daviesia dielsii*	Endangered	Species or species habitat may occur within area
Late Hammer-orchid	*Drakaea confluens*	Endangered	Species or species habitat may occur within area
Mogumber Bell, Narrogin Bell	*Darwinia carnea*	Endangered	Species or species habitat known to occur within area
Narrow curved-leaf Grevillea	*Grevillea curviloba subsp. incurva*	Endangered	Species or species habitat likely to occur within area
Wagin Banksia	*Banksia oligantha*	Endangered	Species or species habitat may occur within area
Swamp Starflower	*Calytrix breviseta subsp. breviseta*	Endangered	Species or species habitat may occur within area
Rare Grevillea	*Grevillea rara*	Endangered	Species or species habitat known to occur within area
Fine-leaved Darwinia	*Darwinia acerosa*	Endangered	Species or species habitat known to occur within area
Splendid Wattle, Dandaragan Wattle	*Acacia splendens*	Endangered	Species or species habitat known to occur within area
chittering Myrtle	*Hypocalymma sylvestre*	Endangered	Species or species habitat known to occur within area
Pythara Grevillea	*Grevillea pythara*	Endangered	Species or species habitat may occur within area
Christine's Grevillea	*Grevillea christineae*	Endangered	Species or species habitat known to occur within area
Beaked Lepidosperma	*Lepidosperma rostratum*	Endangered	Species or species habitat may occur within area
Spiral Bush	*Spirogardnera rubescens*	Endangered	Species or species habitat known to occur within area
Drummond's Conostylis	*Conostylis drummondii*	Endangered	Species or species habitat known to occur within area
null	*Eremophila glabra subsp. chlorella*	Endangered	Species or species habitat known to occur within area
Wing-fruited Lasiopetalum	*Lasiopetalum pterocarpum*	Endangered	Species or species habitat known to occur within area
Prostrate Flame Pea	*Chorizema humile*	Endangered	Species or species habitat may occur within area
Quindanning Spider Orchid, Boddington Spider Orchid	*Caladenia hopperiana*	Endangered	Species or species habitat known to occur within area
Collie Spider Orchid	*Caladenia leucochila*	Endangered	Species or species habitat likely to occur within area
Gingin Wax	*Chamelaucium lullfitzii*	Endangered (listed as *Chamelaucium* sp. Gingin (N.G. Marchant 6))	Species or species habitat likely to occur within area
Sandplain Duck Orchid	*Caleana dixonii*	Endangered (listed as *Paracaleana dixonii)*	Species or species habitat may occur within area

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Threatened flora identified within the Northern Jarrah Forest *(continued)*

Common name	Scientific name	Threatened category	Presence text
Grass Wattle, Chittering Grass Wattle	*Banksia serratuloides subsp. serratuloides*	Vulnerable	Species or species habitat known to occur within area
Southern Serrate Dryandra	*Ptychosema pusillum*	Vulnerable	Species or species habitat may occur within area
Dwarf Pea	*Eleocharis keigheryi*	Vulnerable	Species or species habitat known to occur within area
Keighery's Eleocharis	*Acacia aphylla*	Vulnerable	Species or species habitat known to occur within area
Leafless Rock Wattle	*Anthocercis gracilis*	Vulnerable	Species or species habitat known to occur within area
Slender Tailflower	*Adenanthos pungens subsp. pungens*	Vulnerable	Species or species habitat may occur within area
Spiky Adenanthos	*Conospermum undulatum*	Vulnerable	Species or species habitat known to occur within area
Wavy-leaved Smokebush	*Drakaea micrantha*	Vulnerable	Species or species habitat may occur within area
Dwarf Hammer-orchid	*Diuris micrantha*	Vulnerable	Species or species habitat known to occur within area
Dwarf Bee-orchid	*Asterolasia nivea*	Vulnerable	Species or species habitat likely to occur within area
Bindoon Starbush	*Thomasia montana*	Vulnerable	Species or species habitat known to occur within area
Hill Thomasia	*Calectasia pignattiana*	Vulnerable	Species or species habitat likely to occur within area
Stilted Tinsel Lily	*Tribonanthes purpurea*	Vulnerable	Species or species habitat known to occur within area
Granite Pink	*Banksia squarrosa subsp. argillacea*	Vulnerable	Species or species habitat may occur within area
Whicher Range Dryandra	*Pultenaea pauciflora*	Vulnerable	Species or species habitat known to occur within area
Narrogin Pea	*Diuris drummondii*	Vulnerable	Species or species habitat known to occur within area
Tall Donkey Orchid	*Grevillea flexuosa*	Vulnerable	Species or species habitat known to occur within area
Zig Zag Grevillea	*Morelotia australiensis*	Vulnerable (listed as *Tetraria australiensis*)	Species or species habitat known to occur within area
Southern Tetraria	*Grevillea flexuosa*	Endangered	Species or species habitat known to occur within area

Threatened and migratory (highlighted) fauna identified within the Northern Jarrah Forest

Common name	Scientific name	Threatened category	Class	Presence text
Eastern Curlew, Far Eastern Curlew	*Numenius madagascariensis*	Critically endangered	Bird	Species or species habitat may occur within area
Curlew Sandpiper	*Calidris ferruginea*	Critically endangered	Bird	Species or species habitat may occur within area
Common Greenshank, Greenshank	*Tringa nebularia*	Endangered	Bird	Species or species habitat likely to occur within area
Noisy Scrub-bird, Tjimiluk	*Atrichornis clamosus*	Endangered	Bird	Species or species habitat may occur within area
Australasian Bittern	*Botaurus poiciloptilus*	Endangered	Bird	Species or species habitat known to occur within area
Australian Painted Snipe	*Rostratula australis*	Endangered	Bird	Species or species habitat likely to occur within area
Baudin's Cockatoo, Baudin's Black-Cockatoo, Long-billed Black-cockatoo	*Zanda baudinii*	Endangered (listed as *Calyptorhynchus baudinii*)	Bird	Breeding known to occur within area
Carnaby's Black Cockatoo, Short-billed Black-cockatoo	*Zanda latirostris*	Endangered (listed as Calyptorhynchus latirostris)	Bird	Breeding known to occur within area
Grey Falcon	*Falco hypoleucos*	Vulnerable	Bird	Species or species habitat may occur within area
Malleefowl	*Leipoa ocellata*	Vulnerable	Bird	Species or species habitat known to occur within area
Southern Whiteface	*Aphelocephala leucopsis*	Vulnerable	Bird	Species or species habitat may occur within area
Sharp-tailed Sandpiper	*Calidris acuminata*	Vulnerable	Bird	Species or species habitat likely to occur within area
Forest Red-tailed Black-Cockatoo, Karrak	*Calyptorhynchus banksii naso*	Vulnerable	Bird	Species or species habitat known to occur within area
Blackstriped Dwarf Galaxias, Black-stripe Minnow	*Galaxiella nigrostriata*	Endangered	Fish	Species or species habitat may occur within area
Balston's Pygmy Perch	*Nannatherina balstoni*	Vulnerable	Fish	Species or species habitat likely to occur within area
A short-tongued bee	*Leioproctus douglasiellus*	Critically endangered	Insect	Species or species habitat may occur within area
Western Ringtail Possum, Ngwayir, Womp, Woder, Ngoor, Ngoolangit	*Pseudocheirus occidentalis*	Critically endangered	Mammal	Species or species habitat known to occur within area
Black-flanked Rock-wallaby, Moororong, Black-footed Rock Wallaby	*Petrogale lateralis lateralis*	Endangered	Mammal	Translocated population known to occur within area
Numbat	*Myrmecobius fasciatus*	Endangered	Mammal	Species or species habitat known to occur within area
Woylie	*Bettongia penicillata ogilbyi*	Endangered	Mammal	Species or species habitat known to occur within area

(Continued following page)

Threatened and migratory (■ highlighted) fauna identified within the Northern Jarrah Forest *(continued)*

Common name	Scientific name	Threatened category	Class	Presence text
Red-tailed Phascogale, Red-tailed Wambenger, Kenngoor	*Phascogale calura*	Vulnerable	Mammal	Species or species habitat known to occur within area
Greater Bilby	*Macrotis lagotis*	Vulnerable	Mammal	Translocated population known to occur within area
Quokka	*Setonix brachyurus*	Vulnerable	Mammal	Species or species habitat known to occur within area
Ghost Bat	*Macroderma gigas*	Vulnerable	Mammal	Species or species habitat may occur within area
Chuditch, Western Quoll	*Dasyurus geoffroii*	Vulnerable	Mammal	Species or species habitat known to occur within area
Carter's Freshwater Mussel, Freshwater Mussel	*Westralunio carteri*	Vulnerable	Other	Species or species habitat known to occur within area

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