Resilient Landscapes

National Environmental Science Program

# Expanding Australia's safe havens network to protect non-mammal species

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This publication (and any material sourced from it) should be attributed as: Gould J[1], Southwell D[1], Griffin AS[1] and Hayward MW[1] (2024) *Expanding Australia's safe havens network to protect non-mammal species*. Report to the Resilient Landscapes Hub of the Australian Government's National Environmental Science Program. University of Newcastle. September. CC BY 4.0.

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This report is available on the NESP Resilient Landscapes Hub website: https://nesplandscapes.edu.au/resources/

The Resilient Landscapes Hub is funded by the Australian Government under the National Environmental Science Program. The hub is hosted by The University of Western Australia.

**Disclaimer**

**Acknowledgements**

The authors thank Sarah Legge and John Wonarski for expert advice, Jennifer Pierson and Liana Joseph from the Australian Wildlife Conservancy for advice on species distribution modelling, as well as Katherine Moseby, the Office of the Threatened Species Commissioner, Biodiversity Conservation Division, Environment and Heritage Group, and the Terrestrial Threatened Species Section, Protected Species and Communities Branch for review of drafts.

**Acknowledgement of Country**

We acknowledge the Traditional Owners of Country throughout Australia and recognise their continuing connection to land, waters and culture. We pay our respects to their Elders past and present. Our Indigenous research partnerships are a valued and respected component of National Environmental Science Program research.

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# 1 Executive summary

A key strategy to protect Australian species from introduced species is by reducing their exposure via physical separation. This includes the use of fenced areas and offshore islands — also known as ‘safe havens’.

Separating at-risk native species from their introduced threats allows native populations to persist until management actions enable species to move back into the broader landscape. To date, the network of Australian safe havens has primarily been designed to protect native mammals from unnatural predation pressures from cats and foxes. Now, there is a need to increase the protection of non-mammal species within this network, in part by establishing new havens in areas of suitable habitat. If safe havens are to provide long term coverage, we must consider future shifts in species distributions due to climate change when prioritising locations to add to the safe havens network.

In this report, we performed species distribution modelling with systematic spatial planning to locate high value areas for the placement of future safe havens. This was based on the likely geographic distribution of target native species while accounting for potential shifts caused by climate change and the existing safe haven network. Our list contained 123 non-mammal native species threatened by introduced species. This list included 22 invertebrates, 34 fish, 27 amphibians, 19 reptiles, and 21 birds.

When considering all target species, the highest priority areas occurred across 96 IBRA (Interim Biogeographic Regionalisation for Australia) subregions on mainland Australia. Most areas occurred along the east coast, including pockets in far north Queensland, southern Queensland, northern New South Wales, and northern Victoria. Other high priority pockets were evident in central Australia, the north-east coast of the Northern Territory, and north of Kangaroo Island in South Australia.

The areas identified in the current project represent land area gaps within the current safe havens network that maximise coverage and thus inclusion of non-mammal species. By establishing safe havens within these areas, the capacity of Australia’s safe havens network to buffer native species decline for a diverse assemblage of threatened animals will be improved.

The next phase in expanding the protection of non-mammal species within Australia’s safe havens network must consider the following:

- prioritisation: whether target species are evaluated for protection within future havens is based on threat severity level and extinction risk
- feasibility: the chances of establishing and/or maintaining viable populations within havens, based on species requirements, population size, translocation risks, logistics, and costs
- substitution: for translocation of target species that cannot be protected against key introduced threats in fenced areas, identifying offshore islands that share similar conditions to adjacent areas on the mainland.

# 2 Introduction

## 2.1 Background

Many Australian species are threatened by introduced species, which have driven large population declines and extinctions (Kearney et al. 2019; Woinarski et al. 2019). One noticeable example is the predation threat posed by introduced mammals such as cats (*Felis catus*) and European red foxes (*Vulpes vulpes*), which has resulted in significant declines among Australian mammals (Woinarski et al. 2019). Another example is the introduced mosquito fish (*Gambusia holbrooki*), which has impacted Australian amphibians (Pyke and White 2000).

Introduced species also pose a threat given their roles as competitors, environmental disruptors, poisoners, disease spreaders, and pathogens. For example, introduced rodents compete with arboreal mammals for food resources (McGregor et al. 2022), introduced ungulates such as horses have disrupted native rodent habitat (Eldridge et al. 2019), the introduced cane toad (*Rhinella marina*) has caused rapid declines in reptiles due to toxic consumption (Doody et al. 2014), and the introduced chytrid fungus (*Batrachochytrium dendrobatidis*) has caused widespread mortality among amphibians (Berger et al. 1999).

While native species can persist in the presence of introduced species (Moseby et al. 2019), some do so tenuously and have only avoided total extinction because of human intervention or the existence of populations in areas where such threats occur at low levels (e.g., marginal habitat, habitat hostile to invaders, colonisation fronts/safe havens), or not at all (e.g., on islands). Multiple introduced species acting upon a population simultaneously reduce its resilience and can tip that population into rapid decline (Beranek et al. 2020), while other threatening processes, such as problematic native species, habitat degradation, and climate change may exacerbate the threat posed by introduced species via chains of extinction (Brook et al. 2008; Carey et al. 2012; Didham et al. 2007; Mainka and Howard 2010). Thus, the response of native species to introduced species must not be considered in isolation, but rather in the context of the many factors that may influence their ability to persist in the presence of these introduced threats, including the potential interactions among all threat types they are experiencing (Didham et al. 2007).

There have been substantial efforts made in reducing the pressure of introduced species on susceptible native fauna via means of physical separation, thus allowing for population recovery and preventing future extinction risk (Hoffmann and Broadhurst 2016). These efforts have included managing introduced species presence through physical/chemical controls (e.g., poison-bating, trapping, shooting; Berry et al. 2012; Doherty and Ritchie 2017), as well as biological controls (e.g., viruses; Kerr et al. 2017). This is performed to limit introduced species numbers, keeping them at sufficiently low levels for native species to persist in their presence (Possingham et al. 2004), or to entirely eradicate them so that native populations or species can increase in abundance by re-establishing natural levels of mortality and life history parameters (Hayward et al. 2015; Innes et al. 2015). While control methods have been effective at eliminating introduced species in areas where recolonisation is less likely, such as offshore islands (Dickman 1992), they are not readily viable options for larger areas such as entire countries, as the density and distribution of the introduced threat is far too great for systemic control (Evans et al. 2022).

Alternative approaches to separating native species from their invasive threat include protecting them in:

- intensely managed yet relatively smaller areas
- areas where natural barriers prevent colonisation of introduced threats (e.g., plateaus; Gould et al. 2024)
- enclosures capable of excluding threats using artificial barriers such as fences, or
- a combination of approaches such as exploiting peninsulas where the coastline acts as a natural barrier and partial fencing restricts access from further inland.

These areas are collectively referred to as 'safe havens', where the principal threat of introduced species is naturally absent or it is managed in order to keep numbers low or for total exclusion in perpetuity (Legge et al. 2019; Legge et al. 2018). Thus, safe havens benefit threatened species and aid in recovery in the mid- to long-term by allowing viable populations to persist with reduced extinction risk due to the absence of exposure to introduced species.

Safe havens can be formed in areas where naturally occurring populations still exist, where a species has become locally extinct, or outside of a species' natural range (Smith et al. 2020b). Individuals from natural and/or captive populations can subsequently be translocated to these havens to assist in the reinforcement, reintroduction, or assisted colonisation of areas that are managed for, or free from, introduced threats (Palmer et al. 2020; Scheele et al. 2021). Safe havens offer native animals a reprieve from the threat of introduced species, which can complement other strategies, such as captive breeding, by providing a space where the native animal can be maintained under relatively natural conditions (Legge et al. 2018; Smith et al. 2022).

To date, the Australian safe havens network has primarily been designed using offshore island and fenced mainland enclosures to protect native mammals within the critical weight range from the predation pressure of introduced predators, namely cats and foxes (Burbidge and McKenzie 1989; Kanowski et al. 2018; Moseby et al. 2009), helping to prevent further extinctions within this particular animal group. Ringma et al. (2019) have investigated the adequacy of the network for protecting threatened mammals and expanding protection for this group. However, non-mammalian fauna may also be indirectly benefiting from protection within current havens or could benefit from inclusion within a future safe haven network that is able to reduce exposure to a range of threats beyond cats and foxes. Yet, the extent of protection currently conferred to non-mammal species within the network is low because the existing safe havens either do not contain these species or because enclosures have not been specifically designed to protect against their key threats (Woinarski et al. 2024). For example, current havens that are free of cats and foxes may still house other introduced species that are smaller (e.g., rats and pathogens) as fences are permeable to them. While it is possible to design fenced havens to exclude smaller invaders (e.g., Zealandia in New Zealand; Burns et al. 2012), some invaders may be unavoidable or unmanageable on mainland havens but could be avoided on offshore islands where they are absent or can be eradicated (Russell and Holmes 2015; Stockwell et al. 2015). Thus, establishing new safe havens should consider the existing network of havens, in combination with threatened species currently not protected by the system, and the capacity for each introduced threat to be managed by different safe haven types.

Future shifts in species distributions due to climate change must be also considered when evaluating the capacity for Australia's current safe havens network to protect a wide range of threatened species from introduced species, as well as prioritising the location of new safe havens. While some species are tolerant to a wide range of environmental conditions or able to respond to changing conditions via migration, adaptation, and phenotypic plasticity (Nicotra et al. 2010), others are specialists that occupy small climatic envelopes with little capacity for adapting to rapid changes in conditions (MacLean and Beissinger 2017; Pearce-Higgins et al. 2015; Stefanescu et al. 2011). Human-induced climate change is expected to involve increased temperatures and more variable precipitation, which is likely to alter the location of suitable habitat for species, leading to geographical shifts, expansions or shrinkages in current distributions or isolation (Chen et al. 2011).

Dependent on the severity of future climate change, current havens may not have the capacity to continue offering suitable habitat for species they were designated or designed to protect as the climate envelope of these species moves outside of the haven boundary (Araújo et al. 2004). Thus, there is a risk that positioning new havens that do not consider climate change may cause them to become obsolete in the near future, and for the haven network to see a decline in the number of threatened species they protect. Additionally, climate change is likely to also cause shifts in the distribution of introduced species (e.g., Kearney et al. 2008). Thus, it is vital that the establishment of new safe havens is robust to shifts in the distribution of target native species under a changing climate, that locations are prioritised for where these species are likely to occur and where safe havens are currently absent, and that the current distribution of invading threats is not used as criteria to exclude areas from future inclusion in the network as this may change with climate change or management. Incorporating climate change into the planning of Australia’s future safe havens network will improve the chances of it being part of the solution to the nation’s high rate of anthropogenic extinction, providing resilience to the threatened species from their introduced threats.

## 2.2 Aims

In this study, we identify the best areas for the expansion of Australia’s current network of fenced and offshore island safe havens that prioritises the protection of native non-mammal species threatened by introduced plants, animals and pathogens, as well as problematic native species. We performed species distribution modelling with systematic spatial planning to locate high value areas for the placement of future safe havens based on the likely geographic distribution of target species while accounting for potential shifts caused by climate change and the existing haven network. Our goal is to maximise the protection of non-mammal species within the safe haven network by pinpointing areas of suitable habitat where viable populations are likely to be sustained if safe havens are established, to reduce their risk of extinction as a result of introduced threats.

# 3 Methods

## 3.1 Species identification

We focused on all non-mammal species or sub-species listed as threatened under the *Australian Government's Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act) listed as of June 2023 and susceptible to introduced species and/or problematic native species (Appendix A). This included all susceptible invertebrates, fish, amphibians, reptiles, and birds, including all non-extinct species or sub-species, as well as migratory species which naturally occur within Australia for parts of their life cycle (e.g., non-breeding). Species were identified based on a recent assessment made by Woinarski et al. (2024). We supplemented our list with species not identified by Woinarski et al. (2024), including 3 amphibians from the *Philoria* genus (*P. kundagungan*, *P. richmondensis*, *P. knowlesi*) after expert consultation, and one amphibian species (*Mixophyes australis*) that has recently been described and split from a species (*Mixophyes balbus*) listed by Woinarski et al. (2024); we assumed that all species post-split were impacted equally by the threats posed to the species they were split from. We considered susceptibility at the species level as opposed to population level and did not differentiate threat levels between separate populations; although it is likely that some threats are only impacting some populations. We included species threatened by any introduced or native threat, including microorganisms, plants, and animals, and for any threatening process, including predation, competition, disease, and indirect impacts on populations such as via degradation of habitat quality. Most threats listed by Woinarski et al. (2024) have been identified to the species level, with some only to a general threat type (e.g., weeds).

## 3.2 Species distribution modelling

After identifying priority species, our next goal was to predict their distribution across mainland Australia under climate change. This involved collating occurrence records, obtaining relevant environmental layers based on current conditions and under climate change, fitting species distribution models, mapping the existing safe havens network, and combining maps of predicted distributions into a spatial prioritisation. These steps are outlined in detail below.

## 3.3 Occurrence data

We obtained occurrence records within Australia for all target species using several international/national databases, including Birdlife Australia, Global Biodiversity Information Facility (GBIF), and the Atlas of Living Australia (ALA), as well as state databases, including Queensland WildNet database, New South Wales BioNet Atlas, Biodiversity Databases of South Australia and Victorian Biodiversity Atlas. Species were searched based on current scientific names and synonyms. Records were manually screened for invalid or missing coordinates, for outliers deemed outside of each species' likely range (e.g., middle of the ocean), and for duplicates, which were removed. Occurrence records outside of Australia, such as those for migratory species and those introduced to regions outside of Australia, were excluded. The occurrence of 2 undescribed fish, Malanda rainbowfish, *Melanotaenia* sp, nov*. 'Malanda'*, and Yalmy Galaxias, *Galaxias* sp. nov*. 'Yalmy'*, were approximated based on Species Profile and Threats Database (SPRAT) maps, given the absence of occurrence records.

## 3.4 Current and future environmental predictors

We selected 22 environmental condition covariates thought to drive the distribution of target species, including climatic, environmental, and topographic. Selection of these covariates was based on similar work by Southwell et al. (2022), who fitted SDMs to Australian species affected by the 2019-20 bushfires. We obtained climate variables under current (1970-2000) and future conditions in 2050 from WorldClim. For future climate conditions, we retrieved raster layers for climate covariates derived from 4 models (ACCESS-CM2, CMCC-ESM2, EC-Earth3-Veg, GFDL-ESM4) for the period 2041-2060 under 2 emissions scenarios: ssp126, a low "optimistic" emissions scenario, and ssp370, a moderate to high "likely" emissions scenario. We averaged the climate predictions across models to account for model uncertainty, producing a raster for each of the 2 emissions scenarios. Climatic data differed between current and future datasets while environmental and topographic data remained static. All covariates were resampled to 250 m resolution and transformed to the Australian Albers (GDA94: EPSG 3577) coordinate reference system. A list of covariates along with their units and source can be found in Table 1.

**Table 1 List of environmental condition covariates used in species distribution models for target species.**

| Variable | Units | Description | Source |
|---|---|---|---|
| Mean diurnal temperature range | degrees C | The mean of all the weekly diurnal temperature ranges. Each weekly diurnal range is the difference between that week's maximum and minimum temperature. | WorldClim |
| Isothermality | dimensionless | The mean diurnal range divided by the Annual Temperature Range. Similar to a standard deviation. | WorldClim |
| Mean temperature of warmest quarter | degrees C | The warmest quarter of the year is determined (to the nearest week), and the mean temperature over this period is calculated. | WorldClim |
| Mean temperature of coldest quarter | degrees C | The coldest quarter of the year is determined (to the nearest week), and the mean temperature over this period is calculated. | WorldClim |
| Precipitation of warmest quarter | mm | The warmest quarter of the year is determined (to the nearest week), and the total precipitation over this period is calculated. | WorldClim |
| Precipitation of coldest quarter | mm | The coldest quarter of the year is determined (to the nearest week), and the total precipitation over this period is calculated. | WorldClim |
| Radiation of wettest quarter | W/m2/day | Radiation of Wettest Quarter - The wettest quarter of the year is determined (to the | WorldClim |

| Variable | Units | Description | Source |
|---|---|---|---|
| | | nearest week), and the average radiation over this period is calculated. | |
| Radiation of driest quarter | W/m2/day | Radiation of Driest Quarter - The driest quarter of the year is determined (to the nearest week), and the average radiation over this period is calculated. | WorldClim |
| Moisture Index Seasonality (Coefficient of Variation) | unitless | The Coefficient of Variation is the standard deviation of the weekly moisture index values expressed as a percentage of the mean of those values (i.e. the annual mean). | WorldClim |
| Mean aspect of slope | degrees | Mean aspect of slope | DEM of Australia |
| Elevation | m | Elevation in metres. Potential to enhance this representation of the land by including minor islands from the coastline mask and assigning altitude values near sea-level to updated grid-cells representing low-lying islands and coastal flats. | DEM of Australia |
| Slope | percent | Mean of the 9 second slope values in each 36 second grid cell (%) | DEM of Australia |
| Topographic Wetness Index | dimensionless | Maximum of the Topographic Wetness Index (TWI) values in each 36 second grid cell. TWI was calculated as ln(a/tan ß) where a is the upslope area per unit contour length and tan ß is the local slope. | CSIRO DAP |
| Normalised difference vegetation index | dimensionless | The normalised difference vegetation index. Created via google earth engine 'MODIS/006/MOD13Q1' satellite data. | Google Earth Engine |
| Distance to waterbodies | m | | Geoscience Aus |
| Native vegetation neighbourhood | percent native vegetation | Nearest neighbourhood of native vegetation. Vegetation neighbourhood was analysed using a focal neighbourhood of 5 cells. | NVIS |
| Soil Available Water Capacity | percent | Available water capacity (averaging over 0-5cm, 5-15cm, and 15-30cm depth layers) | CSIRO DAP |
| Soil Bulk Density (TBD: Whole or Fine Earth) | g/cm^3 | Bulk Density of the whole soil (including coarse fragments) in mass per unit volume by a method equivalent to the core method \|\| Bulk Density of the fine earth fraction of the soil (< 2 mm) in mass per unit volume by a method equivalent to the core method (averaging over 0-5cm, 5-15cm, and 15-30cm depth layers) | CSIRO DAP |

| Variable | Units | Description | Source |
|---|---|---|---|
| Soil pH - CaCl2 | unitless | pH of 1:5 soil/0.01M calcium chloride extract (averaging over 0-5cm, 5-15cm, and 15-30cm depth layers) | CSIRO DAP |
| Soil total phosphorus percentage | percent | Total Phosphorus (averaging over 0-5cm, 5-15cm, and 15-30cm depth layers) | CSIRO DAP |
| Soil clay percentage | percent | < 2 um mass fraction of the < 2 mm soil material determined using the pipette method (averaging over 0-5cm, 5-15cm, and 15-30cm depth layers) | CSIRO DAP |
| Soil silt percentage | percent | 2-20 um mass fraction of the < 2 mm soil material determined using the pipette method (averaging over 0-5cm, 5-15cm, and 15-30cm depth layers) | CSIRO DAP |

## 3.5 MaxEnt model fitting

Habitat suitability for target species under current and future climatic conditions was evaluated by fitting separate MaxEnt (Maximum Entropy) models to occurrence data using the R package Dismo (Hijmans et al. 2017). MaxEnt is a species presence-only approach for species distribution modelling that makes predictions on species geographic distribution across a defined area based on the environmental conditions of sites of known occurrence (Phillips et al. 2006), and yields similar results to other models (Hao et al. 2020; Valavi et al. 2022). As we included historical occurrence records, our modelling is not restricted to areas where species may have retreated in the face of introduced threats, such as marginal habitat that might not be the most suitable but which is hostile to invaders. Conversely, our model may identify areas that are deemed suitable but already impacted by habitat alterations and land clearing.

We excluded 2 species from distribution analysis given that they were marine (seastars: *Marginaster littoralis*, *Parvulastra vivipara*). A further 26 species were excluded as they were strictly island species with no occurrence data on the mainland, given that target variables were not available for offshore islands. However, one island invertebrate, *Moggridgea rainbowi*, was able to be included as it is found on Kangaroo Island where environmental data was available for modelling purposes. We also excluded species with less than 20 occurrence records from the MaxEnt modelling process, as well as fish and freshwater species because they likely require a completely different set of environmental variables (e.g. water PH, river size, flow, turbidity) that are not available at a continental scale. Thus, we fitted SDMs to 44 species, including 5 invertebrates, 19 amphibians, 11 reptiles, and 9 birds. Occurrence records were filtered so that there was only 1 record per species per 250 x 250 m cell. For each species, we defined the study area as all states and territories in which occurrence records were present. Within this area, we generated 10,000 random backgrounds points to act as pseudo-absences. Environmental predictors were then associated to occurrence and background points for modelling purposes.

We performed spatial cross-validation to improve model performance by partitioning the study area of each species into equally sized square spatial units using the blockCV package in R (Valavi et al. 2018). This process effectively divides the species occurrence data into spatial folds as opposed to traditional cross-validation, which randomly divides the dataset. Each fold is used for both training and testing of the MaxEnt model as part of an iterative process; k-1 folds are used to train the model, while the fold left out is used to test the model, until all fold combinations have been run as part of the test and train sets. Two threshold-independent metrics, the continuous Boyce Index (Hirzel et al. 2006), and the receiver operating characteristics (ROC) area under the curve (AUC) (Jiménez-Valverde 2012), were averaged across all folds to obtain an overall assessment of the model's predictive performance. AUC scores range from 0 to 1, with a score of 0.5 indicating models that perform no better than chance, and larger scores indicating increasing model performance and thus reliability; according to Phillips et al. (2006), AUC scores 0.7-1 are defined as good. Similarly, the Boyce Index is a metric for evaluating model predictions ranging from -1 to 1, with values above 0 indicating the model consistently predicts presence locations, values less than 0 indicating the model consistently fails to predict presence locations, and values of 0 indicating predictions no better than chance. Cross-validation was also used to tune/optimise the regularisation multiplier parameter until the maximum AUC value was achieved and reduced possible feature types (i.e., linear, quadratic, product, threshold, and hinge) in the final model to prevent overfitting.

## 3.6 Predicting habitat suitability

The MaxEnt model was used to make predictions of the suitability of habitat across mainland Australia based for each species based on current environmental data. The same model was then used to forecast the extent of suitable habitat for species in the future under the 2 emissions scenarios. Species distribution probability maps based on habitat suitability were generated with continuous range values from 0 (lowest suitability) to 1 (highest suitability).

For mainland species where SDMs could not be performed using MaxEnt, such as species with < 20 occurrence records, we estimated areas of likely historic extent by identifying all subregions (Interim Regionalisation for Australia; IBRA7.0; DCCEEW 2023) with records of occurrence. This was performed as bioregions are geographic areas that share similar environmental conditions, geology, and native vegetations (Thackway and Cresswell 1995), thus allowing conservative species distributions to be estimated at a course scale when occurrence data is scarce. We identified all IBRA subregions containing occurrences for 49 excluded species, which were subsequently defined as their distributional extent.

## 3.7 Identifying current safe havens

For this study, we were specifically interested in fenced mainland and offshore islands safe havens. Records of mainland safe havens, including their size and GPS coordinates, were primarily gathered from Legge et al. (2018) and Dickman (2011), as well as online resources for more recent haven establishments and/or expansions. Mainland safe havens that were not fenced or had partial fencing along only some of their perimeters were excluded, as well as fences deemed non-functional by these authors. Similarly, fenced enclosures less than 10 hectares in total area were excluded, as they were deemed too small to allow for viable populations of larger target species to persist. We determined the IBRA subregion in which each mainland fenced safe haven resides (Appendix B).

Fenced havens in Australia have primarily been constructed to exclude introduced mammalian predators such as cats and foxes and have not been specifically designed or are currently able to exclude other introduced species that can bypass the fencelines due to their smaller size (e.g., rodents, plants, and pathogens). We currently do not have data indicating the types of introduced threats that each fenced haven is able to exclude, except for cats and foxes and likely also species in larger size categories (e.g., goats and pigs). Likewise, we do not have data on the presence/absence of introduced threats on island safe havens except for cats/foxes, as identified by Woinarski et al. (2024).

## 3.8 Prioritisation of future safe havens

We prioritised areas for the creation of future safe havens for non-mammal species to complement the existing network using Zonation. Zonation is a spatial planning tool that ranks areas of land based on their value for a particular feature from 0 to 1; in this case future habitat suitability for our target species under future climate change scenarios predicted by MaxEnt modelling, or their bioregion distribution when MaxEnt could not be performed. We averaged predicted habitat suitability scores across the 2 emissions scenarios and imported this map for all target species, or IBRA regions for species that could not be modelled, into Zonation. Areas that provide suitable habitat for more target species and thus likely high species occurrence were ranked higher than those with suitable habitat for fewer species. We masked out cells that are predicted to become urbanised in 2050 using data modelled by Chen et al. (2020) under the ‘fossil-fuelled development’ scenario (SSP5) characterised by high economic growth and reliance on fossil fuels (Kriegler et al. 2017). We did not mask out cells predicted to become cropland, given the capacity for such areas to be of value for native species and their potential to be rehabilitated in the future. We also ’locked in’ IBRA subregions containing the existing safe havens network so that all areas outside of the network were ranked by the predicted suitability of each species already in the network. For example, if existing havens already cover areas predicted to be most suitable for a species under climate change, then this species is less of a priority for new havens than species not covered by the existing network. We used the additive-benefit function (ABF) to rank cells based on species richness, with 1000 cells removed in each iteration without demanding edge removal that prioritises the connectivity of remaining cells. Zonation was run for all target species combined and separately for each taxonomic group, to determine how different species combinations influenced location ranking.

As part of our results, we have visualised species occurrence and area prioritisation at a fine scale based on modelling, but also at a coarse sub-bioregional scale. This is because the best location for new safe havens will be dependent on a multitude of factors, and as a fine scale alone may create a false sense of precision if habitat suitability is considered in isolation (Ringma et al. 2019).

# 4 Results

## 4.1 Target species

Our list initially contained 123 species threatened by invasive species, including 22 invertebrates, 34 fish, 27 amphibians, 19 reptiles, and 21 birds. Altogether, 48 are listed as critically endangered, 45 endangered, 29 vulnerable, and 1 extinct in the wild, representing 30% of all threatened non-mammal animal species in Australia as of 2023. Most of these species occur on or around the mainland (n = 86) or have populations on both the mainland and offshore islands (n = 10). The remaining 27 species are found (i.e. occurrence records) only on offshore islands, including 55% of the invertebrates (n = 12), 21% of the reptiles (n = 4), and 52% of the birds (n = 11). No fish or frogs are found only on offshore islands.

There are 38 different types of introduced species threatening our target species, including 28 animals, 7 plants, and 3 pathogens (Fig. 1). The most frequently listed introduced threat is animal (77%), followed by pathogen (12%) and plant (11%). The most prolific threats are black rats (a threat to 23% of all species), trout (22% of all species), chytrid fungus (21% of all species), pigs (20% of all species), and cats (19% of all species). However, there are significant differences in the types of introduced species threatening the major animal groups, with the greatest threats for invertebrates being black rats, lantana, and wild tobacco, for fish being trout and redfin, for frogs being chytrid and pigs, for reptiles being cats and foxes, and for birds being cats and black rats. Most native species have several listed introduced threats (61%), including some with up to 6 different threats listed.

Most target species are only threatened by introduced species (85%), or both introduced and problematic native species (13%) (Fig. 1). Two bird species (*Lichenostomus melanops cassidix* and *Pardalotus quadragintus*) are only threatened by problematic native species. The most frequently listed problematic native threat is the freshwater yabby (*Cherax destructor*), impacting 3 target species.

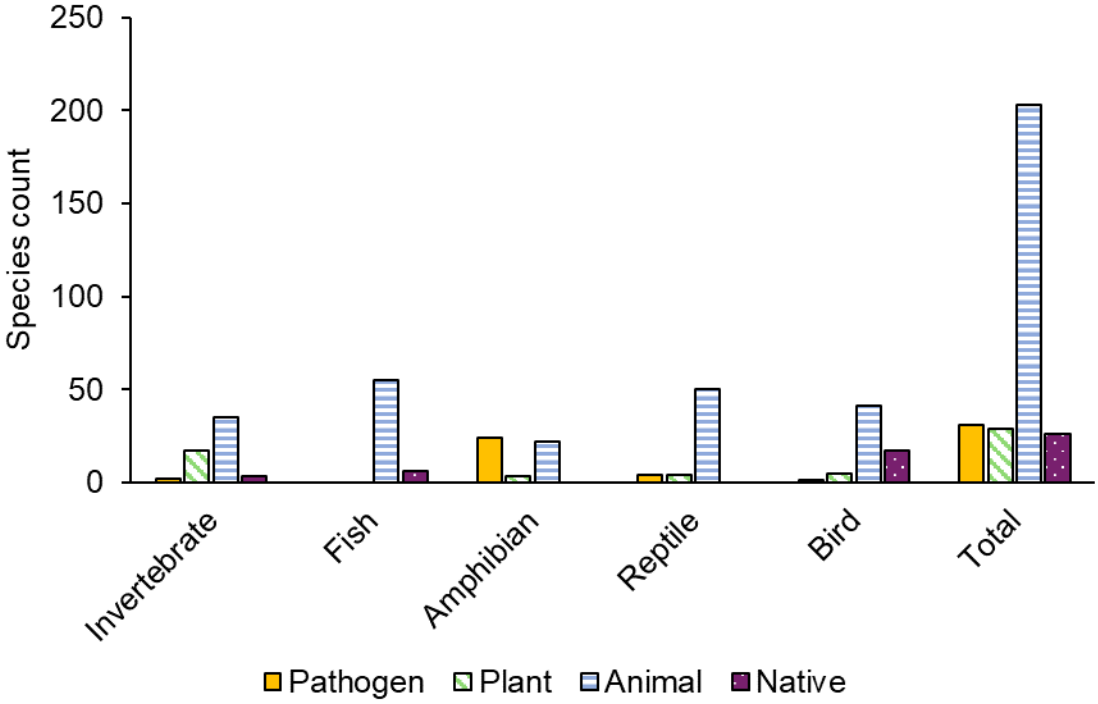
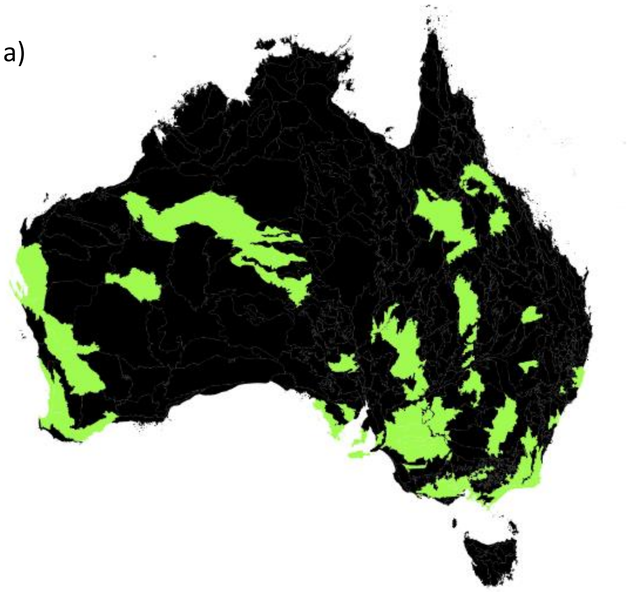


**Figure 1 Count of target species impacted by introduced pathogens, plants and animals, as well as problematic native species.**

## 4.2 Current haven network

We identified 62 fenced safe havens on the Australian mainland, including 52 that have been constructed and 10 that are under construction or proposed (Appendix B). A further 12 fenced havens were excluded as they were below the minimum size threshold of 10 hectares, temporary, partially fenced, or non-functional. Safe havens were found in 44 (11%) IBRA subregions that occur on the mainland (Appendix C); these subregions combined cover 16% of the mainland (Fig. 2).



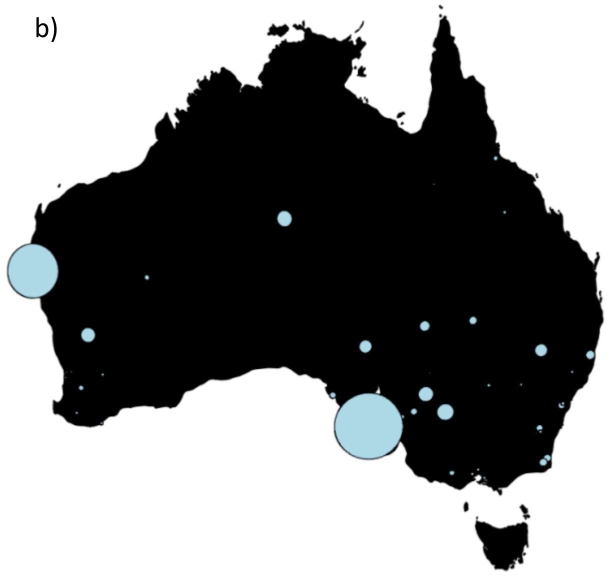
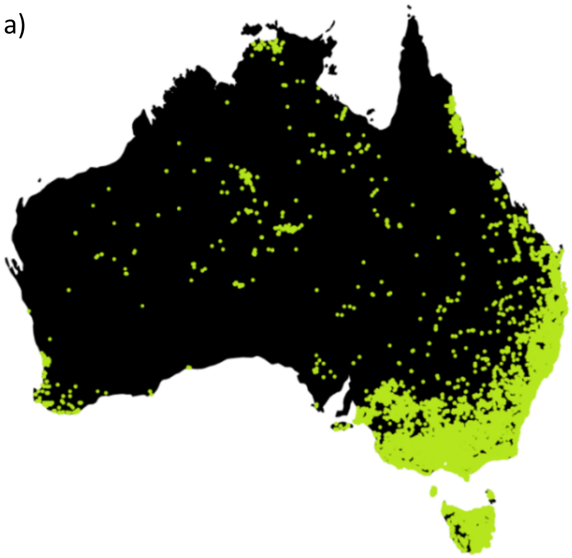


**Figure 2 Location of fenced safe havens on mainland Australia. Maps show a) IBRA subregions containing havens, shown in green, and b) haven location and relative size, exaggerated by 1000 for viewing purposes, shown in blue.**

## 4.3 Species current distributions

There is a strong bias in the location of occurrence records to the south-eastern portion of mainland Australia, including NSW, Victoria, and Tasmania (Fig. 3). Clusters are also apparent in the south-west coast of Western Australia, north-east coast of Queensland and north coast of the Northern territory, with scattered records further inland across several states and territories. Occurrence records for target species cover 267 IBRA subregions (65%), with the greatest number of species found in Highlands-Southern Fall (16 species), South East Coastal Ranges (15 species), and Highlands-Northern Fall (14 species) (Fig. 3).

There are 36 target species currently present on 37 offshore islands, including 12 invertebrates, 2 fish, 2 frogs, 4 reptiles, and 16 birds. Islands range in size from 0.82 to 135,929 hectares (mean = 11,763, SD = 34,937) and range from 0.4 to 2,137 km from the mainland (mean = 784, SD = 786).



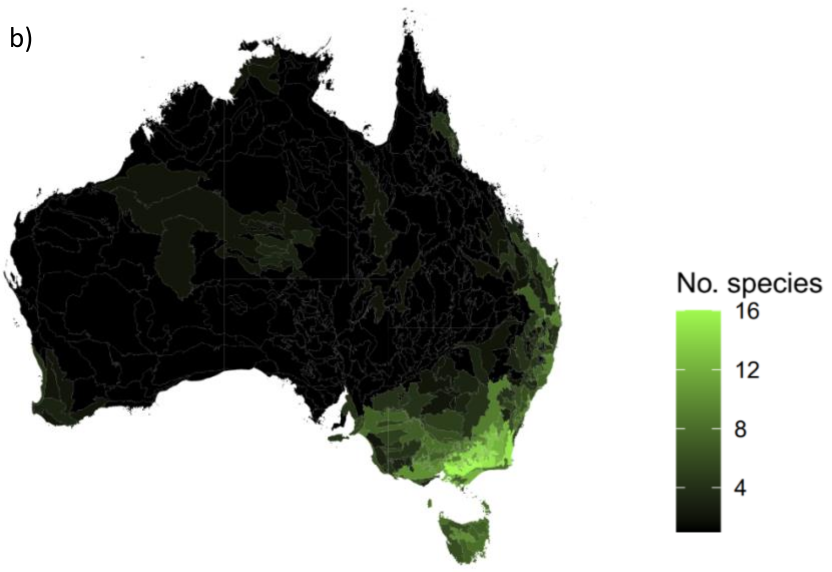


**Figure 3: Occurrence of target species across mainland Australia. Maps show a) presence records for all species, and b) the number of target species found in each IBRA subregion.**

## 4.4 Current safe havens

Only 2 species are known to occur within a current safe haven: the great desert skink (*Liopholis kintorei*) in Newhaven Wildlife Sanctuary and the western swamp tortoise (*Pseudemydura umbrina*) at Twins Swamp and Ellenbrook fenced areas (Woinarski et al. 2024), while the black-eared Miner (*Manorina melanotis*) has been confirmed at Scotia Wildlife Sanctuary but not detected in surveys conducted in 2018-2020 and 2022 (Bauer et al. 2023). Our own analysis showed there are few species with occurrence records in close proximity to Australia's current safe havens network. The average minimum distance to the network is 146 km (SD = 188), ranging from 0.4 to 1128 km. Species occurring within 5 km of a haven include 2 fish (*Galaxiella pusilla, Macquaria australasica*), 3 frogs (*Litoria aurea, Litoria raniformis, Mixophyes iteratus*), 2 reptiles (*Lissolepis coventryi, Pseudemydura umbrina*), and 3 birds (Lat*hamus discolor, Halobaena caerulea, Pterodroma leucoptera leucoptera*).

Few species occur within small fenced safe havens less than 10 hectares in size. This includes 3 *Philoria* species in separate havens designed specifically to exclude pigs (*P. kundagungan, P. richmondensis*, and *P. knowlesi*). Additional havens have been created for one fish; *Galaxias tantangara* against feral horses, and 2 amphibians; *P. corroboree* against chytrid fungus, *P. pengilleyi* against feral horses (Woinarski et al. 2024).

## 4.5 Distribution analysis

After data filtering, we collated 52,539 unique GPS records of species occurrences from data repositories, ranging from 2 to 13,889 records per species. The most records were obtained for frogs (25,007, mean = 926, SD = 2297), followed by birds (18,219, mean = 1822, SD = 4277), reptiles (4,488, mean = 299, SD = 544), fish (4,325, mean = 144, SD = 279), and invertebrates (500, n = 56, SD = 89).

We identified areas ranked by Zonation as the highest priority for inclusion in the network outside of IBRA subregions already containing havens (Fig. 4). When considering all target species, the highest ranking 2% of cells occurred in 82 IBRA subregions (Appendix D). The distance of high priority cells from the current haven network varied considerably, ranging between 4 and 1026 km (mean = 202 km, SD = 181). Most of these cells occurred along the east coast of Australia, including pockets in far north Queensland, southern Queensland, northern New South Wales, and northern Victoria (Fig. 4). Other high priority pockets were evident in central Australia, the north-east coast of the northern Territory, and north of Kangaroo Island in South Australia. No high priority areas occurred in Tasmania. IBRA subregions with the most cells included the Snowy Mountains, McDonnell, Walcha Plateau, Kirrama-Hinchinbrook (Fig. 4; Appendix D)).

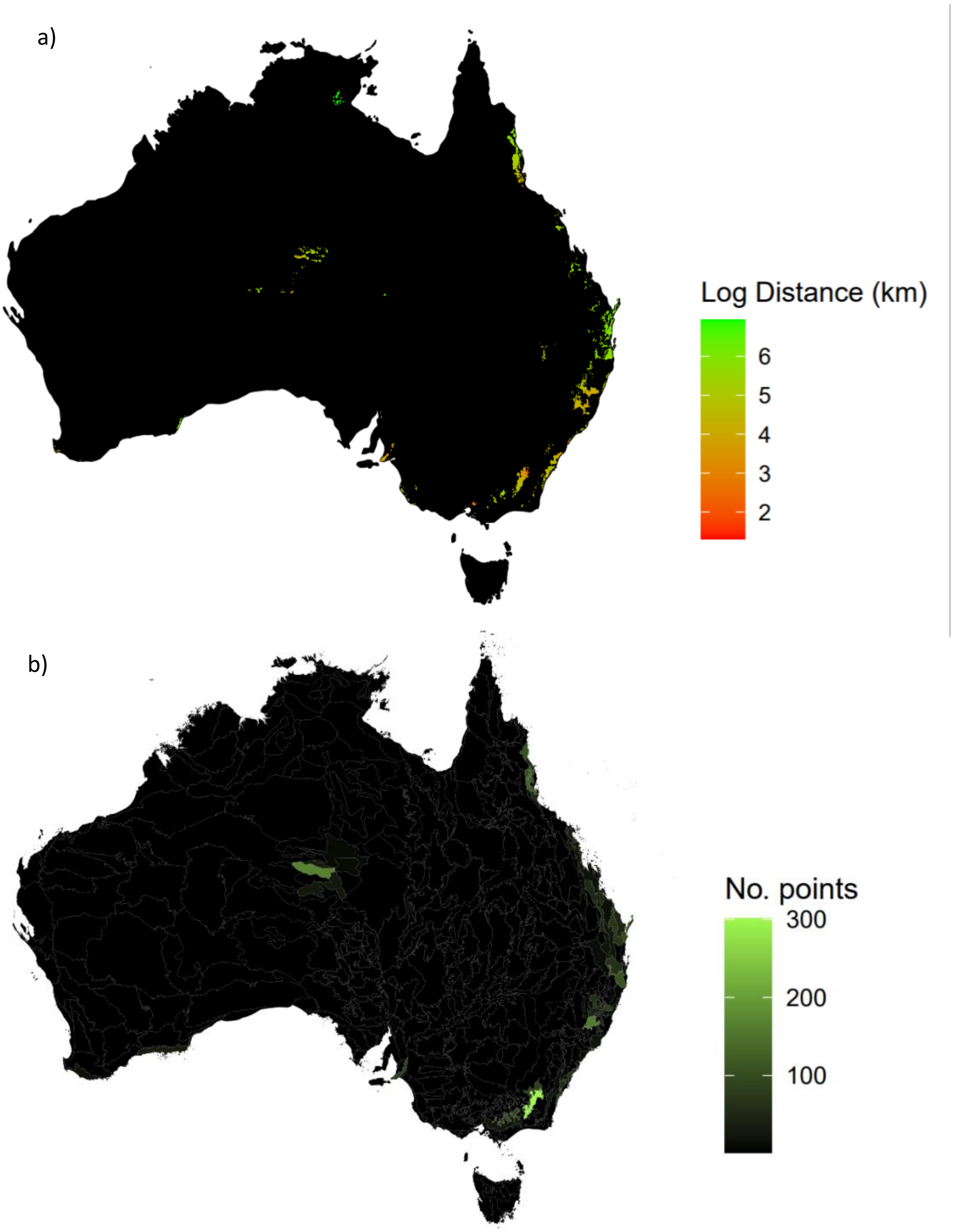


**Figure 4: Priority areas for inclusion in Australia's safe havens network for all target species. Maps show a) the top 2% of ranked cells outside of IBRA subregions that already contain existing havens, colour coded based on the proximity to havens within the current network, and b) IBRA subregions colour coded based on the number of high-ranking cells they contain.**

## 4.6 Prioritisation by taxonomic group

It is apparent that the location of highly suitable areas for haven placement differs when taxonomic groups are analysed separately compared to all target species together (Fig. 5). This is likely the result of taxonomic biases given that some groups have more species than others (e.g., amphibians). Identifying priority areas for each taxonomic group separately may be advantageous as it reduces this bias and allows for more equal coverage between groups.

**Figure 5: Priority areas for inclusion in Australia's safe havens network for each taxonomic group. Maps show the top 2% of ranked cells outside of IBRA subregions that already contain existing havens for a) invertebrate, b) fish, c) amphibians, d) reptiles, and e) birds.**

There are 3 main regions where highly suitable habitat co-occurs for species across multiple taxonomic groups, including the southern portion of Victoria, and pockets along the New South Wales and Queensland coast, and northern Queensland (Fig. 6). These areas should be prioritised for new safe havens are this will allow for maximum coverage of non-mammal species across taxonomic groups so that they will be equally represented within the network

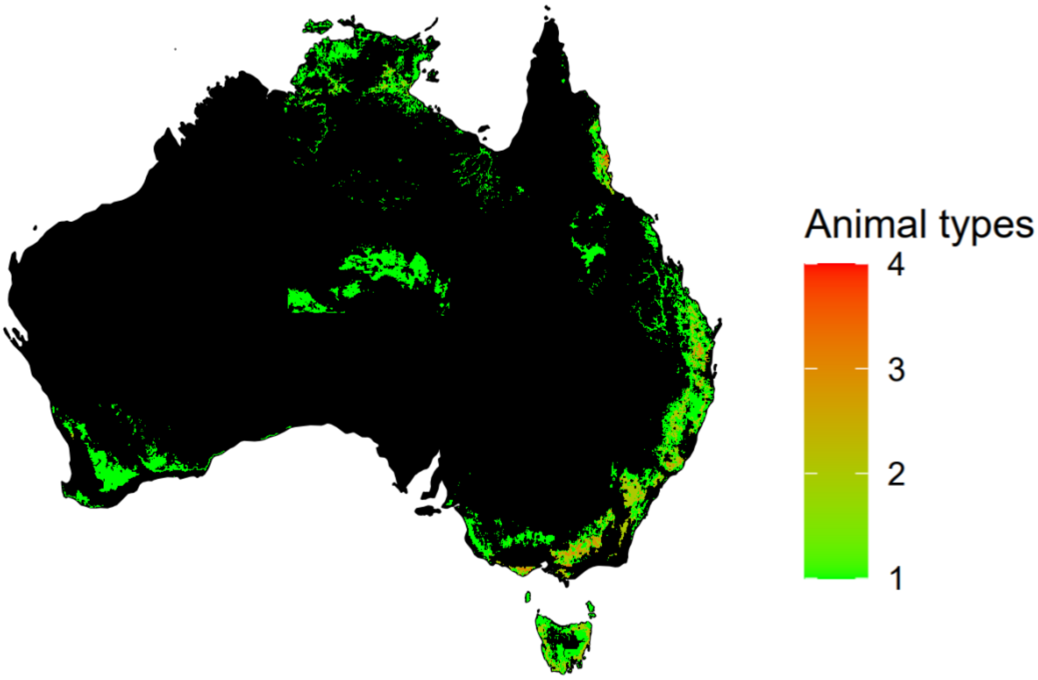


**Figure 6: Priority areas for inclusion in Australia's safe havens network for all taxonomic groups when visualised together. Map shows the top 2% of ranked cells outside of IBRA subregions that already contain existing havens for each taxonomic group after being prioritised separately. The map is colour coded based on whether cells are ranked high for one or several taxonomic groups (i.e. referred to as animal types). Red areas are ranked highly for species across multiple taxonomic groups.**

# 5 Discussion

Australia's current safe havens network has been effective at reducing extinction risk for mammal species threatened by cats and foxes (Legge et al. 2018). However, it is apparent that the network in its current state offers little protection to non-mammal species that are also threatened by cats and foxes or other invasive species; although other non-mammal vertebrates are present in the network and may be benefiting (Roshier et al. 2020). While this indicates that non-mammal species have been able to cling to survival in the absence of the protection afforded by the safe havens network, this does not mean they are not as vulnerable as mammals to extinction from introduced threats or that they will persist without a concerted effort to include them with the network. By accounting for potential changes in species distributions under climate change, we have pinpointed areas on the mainland that are predicted to be most suitable in the future for the placement of safe havens to protect the greatest number of non-mammalian species while complementing the existing haven network and the current protection it affords to target threatened mammal species. By establishing havens within these areas, the capacity of Australia's safe havens network to buffer native species decline for a diverse assemblage of threatened animals will be improved.

Our results indicate that the placement of future havens for non-mammal species should not be based on their proximity to the current safe havens network, given that few of these species are naturally found or present within havens that have been established for mammals. Additionally, there is evidence to suggest that non-mammal species may be at risk of predation by mammals and secondary trophic interactions resulting from invader exclusion within the network (Moseby et al. 2009; Roshier et al. 2020), which could reduce the suitability of existing havens for our target species. The only exception to this would be if there were suitable areas for target species within the current network despite future climate change and thus capacity for translocation, albeit only if risk factors inside these areas are adequately controlled. This is not to suggest that the current network is not benefiting non-mammal species (Roshier et al. 2020; Smith et al. 2020c), instead that the placement of future havens should be based purely on habitat suitability for target species irrespective of their relative position to the current network.

Now that priority areas have been identified, additional data are needed to determine the minimum number of havens required to allow for protection of sufficient habitat for each target species so that they are equally represented in the network. Although beyond the scope of the current project, this is a critical step as our analysis does not provide a count of the total number of target species with suitable habitat within priority areas identified by our analysis. Priority may also want to be given to species based on their threat severity level (e.g., critical endangered species prioritised over vulnerable species), the total number of introduced threats they have, the severity of each introduced threat and all introduced threats combined, the life stage that is impacted by the introduced threat (e.g., eggs versus adults), and the effect of additional threats (e.g., habitat degradation) on extinction risk. Additionally, there needs to be consideration of the haven size required to sustain viable populations that maintain evolutionary potential, which will be influenced by adult size, territory size, and migration needs and thus species-specific. Our results also do not account for the feasibility of translocating each species into new havens and their chances of survival if they are not formed around natural populations, as this may be limited for species with small source populations for a variety of reasons (e.g., small source population size, inadequate habitat knowledge, inadequate knowledge of threats) (Morris et al. 2015). Additionally, the duration or extent to which each species utilise fenced havens must also be considered. For example, most target non-mammal species are non-migratory and remain within a given territory that is used throughout each life stage. However, some migratory species, such as seabirds, may only exploit a given area for short periods of time (e.g. breeding). Species experts should be consulted to verify the habitat contained within proposed fenced havens and whether they satisfy the resource demands of each species. It is apparent that the benefit of establishing future safe havens for non-mammal species and their likelihood of success at allowing viable populations to persist is highly complex and will need to be investigated further now that we have identified priority areas.

What must also be considered is the capacity for exclusion fencing to offer protection against each type of introduced threat. For example, fencing is effective against introduced predators in Australia, such as cats and foxes (Streeting et al. 2023), and larger animal such as pigs and horses, but fencing for smaller animal, such as rodents, is possible but relatively more difficult. In contrast, there is limited capacity for fencing solutions on the mainland to offer protection against pathogens, plants, and birds due to their small size and dispersal ability that cannot be controlled with terrestrial barriers; exceptions include non-airborne pathogens and plants that are dispersed primarily via animal vectors. Further, it is a reality that, for species with multiple threats, fenced enclosures may only offer protection against some but not all threats, although managing one introduced threat may still be adequate to reduce extinction risk. For some aquatic species, fenced havens may not be required if introduced threats have dispersal that is restricted to connected waterways. Instead, maintaining or translocating threatened populations in natural safe havens at higher elevation or in waterways with barriers, such as waterfalls or dams may be a cheaper and more effective solution than fencing (Woinarski et al. 2024).

For species that cannot have their introduced threats excluded on the mainland using fencing, there is an opportunity for protection to be found on offshore island havens (Dickman 1992). This is because the isolation and relatively small size of these land masses reduces the chance of colonisation by invaders and increases the chance of eradication if they are already present. A clear example of this is Broughton Island off the coast of New South Wales, which has remained a natural safe haven for the green and golden bell frog (*Litoria aurea*) against chytrid, despite the island being close to the mainland where this threat persists (Stockwell et al. 2015). We have identified the presence of target species on Australian offshore islands. However, prioritising these islands for the creation of island safe havens is beyond the scope of the current project given that it will require an assessment of several thousand islands where the presence of introduced species are not known and as climatic data for these areas is lacking. Future research is needed to evaluate habitat suitability on islands where species do not currently exist or have been extirpated, and the capacity for them to provide functional space for translocated and/or reintroduced populations while accounting for climate change. It is possible that areas prioritised on the mainland to become fenced havens could by moved to offshore island as areas that share similar conditions (Ringma et al. 2019).

Providing adequate haven coverage for species both within and across taxonomic groups is complex given that resource needs vary considerably. Additionally, some species may share similar resource needs and thus be in direct competition if they are placed together in the same haven. The total number of target non-mammal species that can be sustained together in a given haven must be considered, particularly if they are not naturally co-occurring and can introduce competition or predation pressure (e.g., Roshier et al. 2020), or if their introduced threat requires different fencing designs to prevent ingress. Additionally, there may be cascading system effects of excluding introduced threats and introducing multiple target species that need to be monitored (Linley et al. 2016; Roshier et al. 2020). Fenced havens created for threatened mammals are generally large and contain several species, where haven size may reduce direct competition for resources, particularly if there is sufficient niche partitioning among target species. An alternative may be the creation of boutique 'mini' havens established for single species management. Small, fenced havens have already been created for smaller species in Australia, such as amphibians and fish impacted by herbivores (Woinarski et al. 2024), and have been effective at protecting high quality habitat from these threats (Streeting et al. 2023). Smaller havens are likely to be less expensive and faster to create, as well as easier to manage and patrol compared to larger fenced enclosures, but must be sufficiently large to allow viable populations to persist.

A more nuanced approach for expanding the current safe havens network should thus consider the cost/benefit of multi-species havens but refrain from their use if there is evidence of resource conflict. Under some circumstances, single species havens may be a more effective approach, allowing for the fine-tuning of fenced enclosures so that they are individualised and cater for the specific needs of separate species. Additionally, a primary goal with expanding the network should be to consolidate protection via the establishment of multiple havens per species, especially if they have separate populations that can provide a buffer against stochastic events that could lead to extirpation. Ringma et al. (2019) suggest adequate protection within the network for native species is met when they occur in 6 or more havens. However, this may be reduced for species that occur in more secure wild populations, such as those on islands without key threats in addition to the mainland. Also, smaller species are likely to reach larger population sizes within a safe haven, and so minimum viable population size (total) is likely to be reached with fewer sites.

We excluded urban areas as part of the prioritisation exercise as they likely possess few natural resources for population viability. Yet, small pockets of remanent or artificial habitat are often preserved in developed areas and can be exploited by native species (Valdez et al. 2021). For example, one of the largest remaining colonies of *L. aurea* occurs at Sydney Olympic Park, while some current safe havens (e.g., Royal Botanic Garden, Cranbourne) are in proximity to major Australia cities. It is possible that small, fenced havens could be established in close proximity to urban centres, which requires further investigation before they are to be entirely excluded as candidate sites.

Additional considerations include the cost and logistics of establishing new fenced havens, which are influenced by location (Dickman 2011). Areas closer to the coast and flatter are cheaper and easier to fence, while areas more isolated from urban centres and of rough terrain are going to be more expensive and difficult site choices; although fences for conservation purposes have been created in relatively poorer countries in mountainous areas (e.g., Hayward et al. 2007). Our analysis could be expanded to include land costs into the prioritisation process so that it finds areas that have the highest habitat suitability but are also the cheapest to purchase, while elevation could also be included to find areas that will be easier to fence. Furthermore, fences require regular maintenance and can be damaged by weather or animals, which may allow introduced threats to move across the barrier (Dickman 2011; Gould et al. 2023; Streeting et al. 2023). To reduce costs, there is some opportunity for fencing already installed on agricultural lands to exclude predators and manage grazing by native species (pest or cluster fencing) to play a role in the expansion of the safe havens network (Smith et al. 2020a), although we have not investigated the presence of such fencing in priority areas were target species occur. It appears that there are some crossovers in IBRA subregions that are priority locations for future safe havens for non-mammal species, as identified in the current project, and for mammal species (Ringma et al. 2019), which should be explored further to coordinate the future protection of these different animal groups.

Of course, there are potential limitations associated with the development or expansion of the safe havens network in Australia, including the expense of maintaining fence lines, the loss of anti-predator behaviour in naïve populations, the logistics in the ongoing monitoring of native populations, and preventing recolonisation or incursions by introduced species (Hayward and Kerley 2009). It is also fundamental to recognise that safe havens constitute a small percentage of land area and are not an end-point, but rather a mechanism to gain time to enable conservation managers to address the threats beyond the havens and enable species to move back into the broader landscape (Hayward and Kerley 2009; Hayward et al. 2014).

While exclusion fencing can be an effective means of managing introduced threats that cannot be eradicated, these barriers can themselves be a potential risk to both target and non-target animals (Ferronato et al. 2014; Gould et al. 2023). Indeed, the threat fencing poses to the night parrot (*Pezoporus occidentalis*), a target species on our list, has led to the removal of barbed-wire farm fencing (Queensland Government 2021), and abandonment of a proposed fenced haven for mammals (McLeish 2016). Fencing has also been used to actively exclude native species from high value agricultural lands, preventing migration and fragmenting populations (Lau and Driscol 2019), both of which are threatening processes that could arise for target species with the expansion of the haven network. It is imperative that non-target threatened species within candidate sites are identified, and the potential threat fencing could pose on their survival is thoroughly investigated before any new havens are commissioned.

A limitation of the current project is the lack of occurrence records for several target species, which prevented species distribution modelling from being performed. Instead, we relied on using IBRA subregions for these species as a proxy for the maximum extent of their distribution, leading to an assumption that all areas within a subregion of known occurrence represent suitable habitat. We also did not assess changes in habitat suitability with future climate change within subregions, and thus the extent of occurrence for species analysed this way have not been adjusted accordingly. While this may over-estimate the future extent of suitable habitat for these species, it is apparent from our SDM's of other species that future climate change is likely to result in relatively small shifts in distributions. We have thus assumed that the extent of suitable habitat for all species is likely to remain mostly within the subregions of current occurrence. Additionally, our analysis was restricted to IBRA subregions without havens in the existing network, yet as the current network provides limited protection for our target species it may be beneficial to assess habitat suitability within these regions in finer detail. Finally, we based our results on climate change predictions for 2050 only, but our analysis could be repeated for other periods.

# 6 Conclusion

The areas identified in the current project represent land area gaps within the current safe havens network that maximise coverage and thus inclusion of non-mammal species, complementing the existing network that has primarily been designed for the protection of mammal species. By assessing native species across mainland Australia, our findings should allow for an efficient and nationally coordinated effort to expand the safe havens network to protect non-mammal species, while making it more resilient to environmental change. The sites identified by our modelling are also of general conservation value for target non-mammal species in addition to being ideal for placement of fenced havens. Thus, species management within these sites could potentially take many forms, including those that are complementary, such as translocations, managing invading species numbers, exploiting natural safe havens, and safeguarding these areas from future disturbance by incorporating them within Australia's reserve system.

# Appendix A: Target species table

| **Species name** | **Other names** | **Common name** | **Group** | **EPBCA status** | **Listing date** |
|---|---|---|---|---|---|
| *Cyanoramphus cookii* | *Cyanoramphus novaezelandiae cookii* | Norfolk Island Green Parrot, Tasman Parakeet, Norfolk Island Parakeet | Bird | Endangered | 16/07/2000 |
| *Epthianura crocea tunneyi* | | Alligator Rivers Yellow Chat, Yellow Chat (Alligator Rivers) | Bird | Endangered | 14/12/2006 |
| *Fregetta grallaria grallaria* | | Tasman White-bellied Storm-Petrel, White-bellied Storm-Petrel (Australasian) | Bird | Vulnerable | 16/07/2000 |
| *Halobaena caerulea* | | Blue Petrel | Bird | Vulnerable | 16/07/2000 |
| *Hypotaenidia philippensis andrewsi* | *Gallirallus philippensis andrewsi* | Buff-banded Rail (Cocos (Keeling) Islands), Ayam Hutan | Bird | Endangered | 16/07/2000 |
| *Hypotaenidia sylvestris* | | Lord Howe Woodhen | Bird | Endangered | 15/08/2017 |
| *Lathamus discolor* | | Swift Parrot | Bird | Critically Endangered | 5/05/2016 |
| *Lichenostomus melanops cassidix* | | Helmeted Honeyeater, Yellow-tufted Honeyeater (Helmeted) | Bird | Critically Endangered | 6/11/2014 |
| *Manorina melanotis* | *Manorina flavigula melanotis* | Black-eared Miner | Bird | Endangered | 16/07/2000 |
| *Pachycephala pectoralis xanthoprocta* | | Golden Whistler (Norfolk Island) | Bird | Vulnerable | 16/07/2000 |
| *Pachyptila turtur subantarctica* | | Fairy Prion (southern) | Bird | Vulnerable | 16/07/2000 |
| *Pardalotus quadragintus* | | Forty-spotted Pardalote | Bird | Endangered | 16/07/2000 |
| *Petroica multicolor* | *Petroica multicolor* | Norfolk Island Robin | Bird | Vulnerable | 16/07/2000 |
| *Pezoporus flaviventris* | *Pezoporus wallicus flaviventris* | Western Ground Parrot, Kyloring | Bird | Critically Endangered | 14/05/2013 |
| *Pezoporus occidentalis* | | Night Parrot | Bird | Endangered | 16/07/2000 |
| *Pterodroma heraldica* | *Pterodroma arminjoniana heraldica* | Herald Petrel | Bird | Critically Endangered | 2/07/2002 |
| *Pterodroma leucoptera leucoptera* | *Pterodroma leucoptera* | Gould's Petrel, Australian Gould's Petrel | Bird | Endangered | 16/07/2000 |
| *Pterodroma mollis* | | Soft-plumaged Petrel | Bird | Vulnerable | 16/07/2000 |

| **Species name** | **Other names** | **Common name** | **Group** | **EPBCA status** | **Listing date** |
|---|---|---|---|---|---|
| *Pterodroma neglecta neglecta* | | Kermadec Petrel (western) | Bird | Vulnerable | 16/07/2000 |
| *Sterna vittata bethunei* | | New Zealand Antarctic Tern, Antarctic Tern (New Zealand) | Bird | Endangered | 16/07/2000 |
| *Turnix varius scintillans* | | Painted Button-quail (Houtman Abrolhos) | Bird | Endangered | 31/03/2023 |
| *Bidyanus bidyanus* | | Silver Perch, Bidyan | Fish | Critically Endangered | 21/12/2013 |
| *Brachionichthys hirsutus* | | Spotted Handfish | Fish | Critically Endangered | 11/10/2012 |
| *Chlamydogobius micropterus* | | Elizabeth Springs Goby | Fish | Endangered | 16/07/2000 |
| *Craterocephalus fluviatilis* | | Murray Hardyhead | Fish | Endangered | 16/03/2012 |
| *Galaxias aequipinnis* | | East Gippsland Galaxias | Fish | Critically Endangered | 31/03/2023 |
| *Galaxias auratus* | | Golden Galaxias | Fish | Endangered | 6/06/2005 |
| *Galaxias brevissimus* | | Short-tail Galaxias | Fish | Critically Endangered | 25/03/2023 |
| *Galaxias fontanus* | | Swan Galaxias | Fish | Endangered | 16/07/2000 |
| *Galaxias fuscus* | *Galaxias olidus fuscus* | Barred Galaxias | Fish | Endangered | 16/07/2000 |
| *Galaxias gunaikurnai* | | Shaw Galaxias | Fish | Critically Endangered | 25/03/2023 |
| *Galaxias johnstoni* | | Clarence Galaxias | Fish | Endangered | 16/07/2000 |
| *Galaxias lanceolatus* | | Tapered Galaxias | Fish | Critically Endangered | 25/03/2023 |
| *Galaxias longifundus* | | West Gippsland Galaxias | Fish | Critically Endangered | 25/03/2023 |
| *Galaxias mcdowalli* | | McDowall's Galaxias | Fish | Critically Endangered | 25/03/2023 |
| *Galaxias mungadhan* | | Dargo Galaxias | Fish | Critically Endangered | 25/03/2023 |
| *Galaxias parvus* | | Swamp Galaxias | Fish | Vulnerable | 24/11/2006 |
| *Galaxias pedderensis* | | Pedder Galaxias | Fish | Extinct in the wild | 6/06/2005 |
| *Galaxias* sp. nov. *'Yalmy'* | | Yalmy Galaxias | Fish | Critically Endangered | 25/03/2023 |
| *Galaxias supremus* | | Kosciuszko Galaxias | Fish | Critically Endangered | 25/03/2023 |
| *Galaxias tantangara* | | Stocky Galaxias | Fish | Critically Endangered | 2/03/2021 |
| *Galaxias tanycephalus* | | Saddled Galaxias | Fish | Vulnerable | 16/07/2000 |
| *Galaxias terenasus* | | Roundsnout Galaxias | Fish | Endangered | 25/03/2023 |

| **Species name** | **Other names** | **Common name** | **Group** | **EPBCA status** | **Listing date** |
|---|---|---|---|---|---|
| *Galaxias truttaceus* (Western Australian population) | *Galaxias truttaceus hesperius* | Spotted Galaxias (western subspecies), Western Spotted Galaxias, Western Trout Galaxias | Fish | Endangered | 24/06/2019 |
| *Galaxiella pusilla* | | Eastern Dwarf Galaxias, Dwarf Galaxias | Fish | Vulnerable | 16/07/2000 |
| *Macquaria australasica* | | Macquarie Perch | Fish | Endangered | 16/07/2000 |
| *Melanotaenia eachamensis* | | Lake Eacham Rainbowfish | Fish | Endangered | 16/07/2000 |
| *Melanotaenia* sp. nov. *'Malanda'* | | Malanda Rainbowfish | Fish | Critically Endangered | 5/10/2022 |
| *Nannoperca australis* Murray-Darling Basin lineage | | Southern Pygmy Perch-MDB | Fish | Vulnerable | 13/04/2021 |
| *Paragalaxias dissimilis* | | Shannon Paragalaxias | Fish | Vulnerable | 24/11/2006 |
| *Paragalaxias eleotroides* | | Great Lake Paragalaxias | Fish | Vulnerable | 24/11/2006 |
| *Paragalaxias mesotes* | | Arthurs Paragalaxias | Fish | Endangered | 6/06/2005 |
| *Pseudomugil mellis* | | Honey Blue-eye | Fish | Vulnerable | 16/07/2000 |
| *Scaturiginichthys vermeilipinnis* | | Redfin Blue Eye, Redfin Blue-eye | Fish | Endangered | 16/07/2000 |
| *Thymichthys politus* | | Red Handfish | Fish | Critically Endangered | 11/10/2012 |
| *Litoria aurea* | | Green and Golden Bell Frog | Frog | Vulnerable | 16/07/2000 |
| *Litoria booroolongensis* | | Booroolong Frog | Frog | Endangered | 18/12/2007 |
| *Litoria castanea* | | Yellow-spotted Tree Frog, Yellow-spotted Bell Frog | Frog | Critically Endangered | 24/06/2019 |
| *Litoria daviesae* | | Davies' Tree Frog | Frog | Vulnerable | 15/03/2023 |
| *Litoria dayi* | *Nyctimystes dayi* | Australian Lace-lid, Lace-eyed Tree Frog | Frog | Vulnerable | 24/06/2019 |
| *Litoria kroombitensis* | | Kroombit Tree Frog | Frog | Critically Endangered | 24/06/2019 |
| *Litoria littlejohni* | | Littlejohn's Tree Frog, Heath Frog | Frog | Endangered | 18/02/2022 |
| *Litoria lorica* | | Armoured Mistfrog | Frog | Critically Endangered | 1/02/2007 |
| *Litoria nyakalensis* | | Mountain Mistfrog | Frog | Critically Endangered | 1/02/2007 |
| *Litoria piperata* | | Peppered Tree Frog | Frog | Vulnerable | 16/07/2000 |
| *Litoria raniformis* | | Growling Grass Frog, Southern Bell Frog, Green | Frog | Vulnerable | 16/07/2000 |

| Species name | Other names | Common name | Group | EPBCA status | Listing date |
|---|---|---|---|---|---|
| | | and Golden Frog, Warty Swamp Frog | | | |
| *Litoria spenceri* | | Spotted Tree Frog | Frog | Critically Endangered | 24/11/2021 |
| *Litoria verreauxii alpina* | | Alpine Tree Frog, Verreaux's Alpine Tree Frog | Frog | Vulnerable | 16/07/2000 |
| *Litoria watsoni* | | Watson's Tree Frog | Frog | Endangered | 18/02/2022 |
| *Mixophyes australis* | | Southern Stuttering Frog | Frog | Unlisted | |
| *Mixophyes balbus* | | Stuttering Frog, Southern Barred Frog (in Victoria) | Frog | Vulnerable | 16/07/2000 |
| *Mixophyes fleayi* | | Fleay's Frog | Frog | Endangered | 16/07/2000 |
| *Mixophyes iteratus* | | Giant Barred Frog, Southern Barred Frog | Frog | Vulnerable | 13/11/2021 |
| *Philoria frosti* | | Baw Baw Frog | Frog | Critically Endangered | 24/06/2019 |
| *Philoria kundagungan* | | Mountain Frog | Frog | Endangered | 13/11/2021 |
| *Philoria richmondensis* | | Richmond Range Sphagnum Frog | Frog | Endangered | 13/11/2021 |
| *Philoria knowlesi* | | Mount Ballow Mountain Frog | Frog | Endangered | 1/12/2023 |
| *Pseudophryne corroboree* | | Southern Corroboree Frog | Frog | Critically Endangered | 6/04/2013 |
| *Pseudophryne pengilleyi* | | Northern Corroboree Frog | Frog | Critically Endangered | 6/04/2013 |
| *Taudactylus eungellensis* | | Eungella Day Frog | Frog | Endangered | 16/07/2000 |
| *Taudactylus pleione* | | Kroombit Tinker Frog, Pleione's Torrent Frog | Frog | Critically Endangered | 18/01/2012 |
| *Taudactylus rheophilus* | | Tinkling Frog | Frog | Critically Endangered | 24/11/2021 |
| *Advena campbellii* | *Advena campbelli* | Campbell's Helicarionid Land Snail, Campbell's Keeled Glass-snail | Invertebrate | Critically Endangered | 8/01/2009 |
| *Cherax tenuimanus* | *Chaeraps tenuimanus* | Hairy Marron, Margaret River Hairy Marron, Margaret River Marron | Invertebrate | Critically Endangered | 18/08/2006 |
| *Dryococelus australis* | | Lord Howe Island Phasmid, Land Lobster | Invertebrate | Critically Endangered | 23/07/2002 |
| *Euastacus dharawalus* | | Fitzroy Falls Spiny Crayfish | Invertebrate | Critically Endangered | 7/12/2016 |
| *Gudeoconcha sophiae magnifica* | | Magnificent Helicarionid Land Snail | Invertebrate | Critically Endangered | 8/01/2009 |
| *Marginaster littoralis* | | Derwent River Seastar | Invertebrate | Critically Endangered | 30/06/2009 |
| *Mathewsoconcha grayi ms* | | Gray's Helicarionid Land Snail | Invertebrate | Critically Endangered | 8/01/2009 |

| Species name | Other names | Common name | Group | EPBCA status | Listing date |
|---|---|---|---|---|---|
| *Mathewsoconcha phillipii* | | Phillip Island Helicarionid Land Snail | Invertebrate | Critically Endangered | 8/01/2009 |
| *Mathewsoconcha suteri* | | Suter's Striped Glass-snail | Invertebrate | Critically Endangered | 8/01/2009 |
| *Moggridgea rainbowi* | | Kangaroo Island Micro-trapdoor Spider | Invertebrate | Endangered | 22/04/2022 |
| *Mystivagor mastersi* | | Masters' Charopid Land Snail | Invertebrate | Critically Endangered | 8/01/2009 |
| *Oreixenica ptunarra* | | Ptunarra Brown, Ptunarra Brown Butterfly, Ptunarra Xenica | Invertebrate | Endangered | 24/01/2014 |
| *Parvulastra vivipara* | *Patiriella vivipara* | Tasmanian Live-bearing Seastar | Invertebrate | Vulnerable | 30/06/2009 |
| *Placostylus bivaricosus* | | Lord Howe Flax Snail, Lord Howe Placostylus | Invertebrate | Endangered | 15/11/2005 |
| *Pseudocharopa ledgbirdi* | | Mount Lidgbird Charopid Land Snail | Invertebrate | Critically Endangered | 8/01/2009 |
| *Pseudocharopa whiteleggei* | | Whitelegge's Land Snail | Invertebrate | Critically Endangered | 8/01/2009 |
| *Pseudococcus markharveyi* | | Banksia montana mealybug | Invertebrate | Critically Endangered | 11/05/2018 |
| *Quintalia stoddartii* | | Stoddart's Helicarionid Land Snail | Invertebrate | Critically Endangered | 8/01/2009 |
| *Semotrachia euzyga* | | a land snail | Invertebrate | Endangered | 18/08/2006 |
| *Sinumelon bednalli* | | Bednall's Land Snail | Invertebrate | Endangered | 18/08/2006 |
| *Thaumatoperla alpina* | | Alpine Stonefly | Invertebrate | Endangered | 31/03/2011 |
| *Trioza barrettae* | | Banksia brownii Plant-louse | Invertebrate | Endangered | 24/06/2019 |
| *Acanthophis hawkei* | | Plains Death Adder | Reptile | Vulnerable | 11/05/2012 |
| *Christinus guentheri* | | Lord Howe Island Gecko, Lord Howe Island Southern Gecko | Reptile | Vulnerable | 16/07/2000 |
| *Cryptoblepharus egeriae* | | Christmas Island Blue-tailed Skink, Blue-tailed Snake-eyed Skink | Reptile | Critically Endangered | 3/01/2014 |
| *Elseya albagula* | | Southern Snapping Turtle, White-throated Snapping Turtle | Reptile | Critically Endangered | 7/11/2014 |
| *Elseya lavarackorum* | | Gulf Snapping Turtle | Reptile | Endangered | 16/07/2000 |
| *Elusor macrurus* | | Mary River Turtle, Mary River Tortoise | Reptile | Endangered | 16/07/2000 |
| *Lepidodactylus listeri* | | Lister's Gecko, Christmas Island Gecko | Reptile | Critically Endangered | 3/01/2014 |
| *Liopholis guthega* | | Guthega Skink | Reptile | Endangered | 23/02/2011 |

| **Species name** | **Other names** | **Common name** | **Group** | **EPBCA status** | **Listing date** |
|---|---|---|---|---|---|
| *Liopholis kintorei* | | Great Desert Skink, Tjakura, Warrarna, Mulyamiji | Reptile | Vulnerable | 16/07/2000 |
| *Liopholis montana* | | Mountain Skink | Reptile | Endangered | 10/08/2022 |
| *Lissolepis coventryi* | | Swamp Skink, Eastern Mourning Skink | Reptile | Endangered | 25/03/2023 |
| *Myuchelys purvisi* | | Purvis' Turtle | Reptile | Endangered | 15/03/2023 |
| *Nangura spinosa* | | Nangur Spiny Skink | Reptile | Critically Endangered | 18/12/2007 |
| *Oligosoma lichenigerum* | | Lord Howe Island Skink | Reptile | Vulnerable | 16/07/2000 |
| *Pseudemydura umbrina* | | Western Swamp Tortoise | Reptile | Critically Endangered | 6/07/2004 |
| *Pseudomoia cryodroma* | | Alpine Bog Skink, Alpine Bog-skink | Reptile | Endangered | 25/03/2023 |
| *Rheodytes leukops* | | Fitzroy River Turtle, Fitzroy Tortoise, Fitzroy Turtle, White-eyed River Diver | Reptile | Vulnerable | 16/07/2000 |
| *Wollumbinia belli* | *Wollumbinia bellii, Myuchelys belli* | Bell's Turtle, Western Sawshelled Turtle, Namoi River Turtle, Bell's Saw-shelled Turtle | Reptile | Endangered | 15/03/2023 |
| *Wollumbinia georgesi* | *Myuchelys georgesi* | Georges' Snapping Turtle, Bellinger River Snapping Turtle, Georges Helmeted Turtle | Reptile | Critically Endangered | 7/12/2016 |

# Appendix B: Fenced safe havens

| Fenced Haven | Area (hectares) | Longitude | Latitude | Status | IBRA Subregion | State |
|---|---|---|---|---|---|---|
| Great Southern Ark - Yorke Peninsula | 148800 | 137.1435 | -35.05417 | In construction | Southern Yorke | SA |
| Peron | 100000 | 113.55 | -25.833 | non-functional | Wooramel | WA |
| Dudley Peninsula | 38400 | 138.0353 | -35.8083 | future | Kangaroo Island | SA |
| Mallee Cliffs | 9600 | 142.5369 | -34.2171 | functional | South Olary Plain | NSW |
| Newhaven | 9400 | 131.2282 | -22.7299 | functional | Mackay | NT |
| Scotia | 7840 | 141.163 | -33.155 | functional | South Olary Plain | NSW |
| Mt Gibson | 7830 | 117.419 | -29.641 | functional | Tallering | WA |
| Arid Recovery | 6000 | 136.918 | -30.325 | functional | Roxby | SA |
| Pilliga | 5800 | 149.2662 | -30.5461 | functional | Pilliga Outwash | NSW |
| Wild Deserts in Sturt National Park | 4000 | 141.08217 | -29.10711 | functional | Strzelecki Desert | NSW |
| Ngambaa Nature Reserve | 3000 | 152.71917 | -30.81889 | In construction | Macleay Hastings | NSW |
| Currawinya | 2500 | 144.478 | -28.783 | non-functional? | West Warrego | QLD |
| Nungatta in South-East Forest National Park | 2084 | 149.41577 | -37.20567 | future | East Gippsland Lowlands | NSW |
| Eden Bombala Region | 2000 | 149.6927 | -36.95494 | future | South East Coastal Ranges | NSW |
| Orchard Hills | 1700 | 150.71283 | -33.81784 | future | Cumberland | NSW |
| Banrock Station | 1600 | 140.32397 | -34.18708 | Functional | Murray Scroll Belt | SA |
| Mulligan's Flat (including Goorooyarroo) | 1555 | 149.158 | -35.163 | Functional | Murrumbateman | ACT |
| Venus Bay Conservation Park | 1460 | 134.621 | -33.21 | non-functional? | Talia | SA |

| | | | | | | |
|---|---|---|---|---|---|---|
| Heirisson Prong | 1200 | 113.382 | -26.086 | non-functional | Edel | WA |
| Matuwa (ex-Lorna Glen) | 1100 | 121.555 | -26.225 | functional | Carnegie | WA |
| Yookamurra Sanctuary | 1090 | 139.457 | -34.519 | functional | Murray Mallee | SA |
| Dryandra | 1000 | 116.932 | -32.782 | functional | Northern Jarrah Forest | WA |
| Tiverton | 1000 | 143.001 | -37.831 | functional | Victorian Volcanic Plain | VIC |
| Mt Zero-Taravale | 1000 | 146.0679 | -19.1418 | Functional | Broken River | QLD |
| Mallee Refuge | 800 | 136.817 | -33.196 | functional | Eyre Hills | SA |
| Epping Forest | 600 | 146.708 | -22.3496 | not cat proof | Belyando Downs | QLD |
| Yathong Nature Reserve | 555 | 145.58389 | -32.6343 | future | Barnato Downs | NSW |
| Yiraaldiya National Park (formerly Shanes Park) | 555 | 150.79854 | -33.71248 | future | Cumberland | NSW |
| Castlereagh Nature Reserve | 495 | 150.75681 | -33.6818 | future | Cumberland | NSW |
| Wadderin | 430 | 118.445 | -31.997 | functional | Merredin | WA |
| Mount Rothwell | 420 | 144.435 | -37.898 | functional | Central Victorian Uplands | VIC |
| Perup | 420 | 116.631 | -34.27 | functional | Southern Jarrah Forest | WA |
| Barrington Tops | 400 | 151.452 | -31.834 | functional | Barrington | NSW |
| Woodlands Historic Park | 400 | 144.846 | -37.637 | functional | Central Victorian Uplands | VIC |
| Wandiyali-Environa | 400 | 149.226 | -35.388 | functional | Monaro | NSW |
| Genaren Hill | 390 | 147.864 | -32.588 | non-functional? | Lower Slopes | NSW |
| Waychinicup | 380 | 118.359 | -34.886 | functional | Fitzgerald | WA |
| Kangaroo Island Land For Wildlife | 370 | 136.906 | -35.7 | functional | Kangaroo Island | SA |
| Western River Refuge | 369 | 136.77222 | -35.82336 | Functional | Kangaroo Island | SA |
| Royal Botanic Garden Cranbourne | 360 | 145.274 | -38.129 | functional | Gippsland Plain | VIC |
| Harry Waring Marsupial Reserve | 254 | 115.83265 | -32.16645 | Functional | Perth | WA |
| Julia Creek Aerodome | 250 | 141.722 | -20.668 | functional | Central Downs | QLD |
| Karakamia | 250 | 116.254 | -31.821 | functional | Northern Jarrah Forest | WA |
| Whiteman Park | 200 | 115.92 | -31.851 | functional | Perth | WA |
| Living Desert Flora and Fauna Sanctuary | 180 | 141.46315 | -31.90218 | Functional | Barrier Range | NSW |

| | | | | | | |
|---|---|---|---|---|---|---|
| Twin Swamps Nature Reserve | 150 | 116.01586 | -31.72267 | Functional | Perth | WA |
| Little Desert Nature Lodge | 140 | 141.66757 | -36.45479 | Functional | Lowan Mallee | VIC |
| Roger Underwood NR | 130 | 148.851 | -27.6126 | functional | Weribone High | QLD |
| Richard Underwood Nature Refuge | 130 | 148.851 | -27.6126 | Functional | Weribone High | QLD |
| Tidbinbilla | 120 | 148.9074 | -35.4544 | functional | Murrumbateman | ACT |
| APY Lands Pintji | 100 | 132.346 | -26.188 | functional | Tieyon | SA |
| Hamilton Community Parkland | 100 | 142.023 | -37.723 | functional | Victorian Volcanic Plain | VIC |
| Watarrka National Park | 100 | 131.56987 | -24.26663 | Functional | Watarrka | NT |
| Nangeen | 50 | 117.683 | -31.84 | functional | Merredin | WA |
| Yelverton Brook Conservation Sanctuary | 40 | 115.16873 | -33.75177 | Functional | Perth | WA |
| Mt Vandyke / Banbangil Fenced Nature Sanctuary (Cobboboonee NP) | 35.4 | 141.41375 | -38.06487 | Functional | Victorian Volcanic Plain | VIC |
| Cleland Wildlife Park | 35 | 138.695 | -34.96582 | Functional | Mount Lofty Ranges | SA |
| Ellen Brook Nature Reserve | 34 | 116.0351 | -31.75344 | Functional | Perth | WA |
| Warrawong Sanctuary | 34 | 138.7358 | -35.03652 | Functional | Mount Lofty Ranges | SA |
| Australia Walkabout Wildlife Park (Calga springs sanctuary) | 32 | 151.22312 | -33.42392 | Functional | Pittwater | NSW |
| Nangak Tamboree (La Trobe) Melbourne Widllife Sanctuary | 30 | 145.05093 | -37.71626 | Functional | Gippsland Plain | VIC |
| Wilsons Prom | | 146.3333 | -38.9166 | future | Wilsons Promontory | VIC |

# Appendix C: IBRA subregions with havens

| IBRA Subregion | Number of havens |
|---|---|
| Perth | 5 |
| Cumberland | 3 |
| Kangaroo Island | 3 |
| Victorian Volcanic Plain | 3 |
| Central Victorian Uplands | 2 |
| Gippsland Plain | 2 |
| Merredin | 2 |
| Mount Lofty Ranges | 2 |
| Murrumbateman | 2 |
| Northern Jarrah Forest | 2 |
| South Olary Plain | 2 |
| Weribone High | 2 |
| Barnato Downs | 1 |
| Barrier Range | 1 |
| Barrington | 1 |
| Belyando Downs | 1 |
| Broken River | 1 |
| Carnegie | 1 |
| Central Downs | 1 |
| East Gippsland Lowlands | 1 |
| Edel | 1 |
| Eyre Hills | 1 |
| Fitzgerald | 1 |
| Lowan Mallee | 1 |
| Lower Slopes | 1 |
| Mackay | 1 |
| Macleay Hastings | 1 |
| Monaro | 1 |
| Murray Mallee | 1 |
| Murray Scroll Belt | 1 |
| Pilliga Outwash | 1 |
| Pittwater | 1 |
| Roxby | 1 |
| South East Coastal Ranges | 1 |
| Southern Jarrah Forest | 1 |
| Southern Yorke | 1 |
| Strzelecki Desert | 1 |
| Talia | 1 |

| | |
|---|---|
| Tallering | 1 |
| Tieyon | 1 |
| Watarrka | 1 |
| West Warrego | 1 |
| Wilsons Promontory | 1 |
| Wooramel | 1 |

# Appendix D: Priority IBRA subregions

| IBRA Subregion | No. priority points |
|---|---|
| Snowy Mountains | 301 |
| McDonnell | 167 |
| Walcha Plateau | 159 |
| Kirrama-Hinchinbrook | 124 |
| Scenic Rim | 109 |
| Daintree-Bloomfield | 109 |
| Bellenden Ker-Lamb | 107 |
| Atherton | 105 |
| Great Sandy | 91 |
| Fleurieu | 86 |
| Bondo | 84 |
| Victorian Alps | 83 |
| Chaelundi | 83 |
| Bateman | 78 |
| Gympie Block | 71 |
| Sydney Cataract | 67 |
| Moreton Basin | 63 |
| Glenn Innes-Guyra Basalts | 60 |
| Ettrema | 55 |
| Mount Morgan Ranges | 51 |
| Herbert | 48 |
| Comboyne Plateau | 48 |
| Wongwibinda Plateau | 46 |
| Burnett-Curtis Coastal Lowlands | 46 |
| Macalister | 41 |
| Armidale Plateau | 38 |
| Illawarra | 35 |
| Recherche | 32 |
| Nightcap | 32 |
| Mount Chapple | 30 |
| Upper Manning | 29 |
| Kybeyan-Gourock | 27 |
| Henbury | 27 |
| Proserpine-Sarina Lowlands | 26 |
| Brisbane-Barambah Volcanics | 24 |
| Ebor Basalts | 22 |
| Karuah Manning | 21 |
| Highlands-Southern Fall | 21 |
| South Burnett | 20 |
| Moss Vale | 19 |
| Clarke-Connors Ranges | 19 |
| Yuraygir | 17 |

| | |
|---|---|
| Warren | 17 |
| Marlborough Plains | 17 |
| Coffs Coast and Escarpment | 15 |
| Burnett-Curtis Hills and Ranges | 15 |
| Paluma-Seaview | 14 |
| Kanangra | 14 |
| Eastern Darling Downs | 14 |
| Wyong | 13 |
| Moredun Volcanics | 13 |
| Bungonia | 13 |
| Round Mountain | 11 |
| Hartz Range | 11 |
| Eastern Nandewars | 11 |
| Atartinga | 11 |
| Tully | 10 |
| Deepwater Downs | 10 |
| Clarence Lowlands | 9 |
| Carrai Plateau | 9 |
| Yarrowyck-Kentucky Downs | 8 |
| Southern Flinders | 6 |
| Northeast Forest Lands | 6 |
| Boomer Range | 5 |
| Dawson River Downs | 4 |
| Wollemi | 3 |
| Washpool | 3 |
| Otway Plain | 3 |
| Innisfail | 3 |
| Herberton-Wairuna | 3 |
| Burragorang | 3 |
| Bundarra Downs | 3 |
| Woodenbong | 2 |
| Whitsunday | 2 |
| Oberon | 2 |
| Isaac-Comet Downs | 2 |
| West Balonne Plains | 1 |
| Mummel Escarpment | 1 |
| Macleay Gorges | 1 |
| Lucindale | 1 |
| Hodgkinson Basin | 1 |
| Finke River | 1 |

# Glossary

| Term | Definition |
|---|---|
| ALA | Atlas of Living Australia |
| EPBC Act | Australian Government’s Environment Protection and Biodiversity Conservation Act |
| GBIF | Global Biodiversity Information Facility |
| IBRA | Interim Regionalisation for Australia |
| NESP | National Environmental Science Program |
| SDM | Species distribution model |
| SPRAT | Species Profile and Threats Database |

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