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Australian Frog Atlas: Species' Distribution Maps Informed by the FrogID Dataset

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Abstract. We use data from the citizen science project FrogID, comprised of expert-validated, spatially accurate occurrence records of frog species across Australia, to map the known distributions of Australia's frogs. We combined over half a million occurrence records of 209 species from the FrogID dataset with expert-checked occurrence data from the national biodiversity data aggregate (Atlas of Living Australia) and published literature, to create distribution maps for all 247 native frog species known from Australia and the introduced cane toad (*Rhinella marina*). These maps represent the most up-to-date, accurate and detailed set of Australian frog species maps available, and reveal species richness patterns across the continent. They are an Open Access resource for researchers, conservation practitioners and land managers, with the aim of better understanding and conserving Australia's frogs. This is version one of the Australian Frog Atlas, which we expect to update on an approximately annual basis. The Australian Frog Atlas maps—as shapefiles and in KML format—are published online as an Open Access supplemental dataset (see Cutajar *et al*., 2021).

Introduction

To mitigate biodiversity declines, a good understanding of species' distributions is required (Fjeldsa & Rahbek, 1997; Graham *et al.,* 2004). However, such knowledge is reliant on adequate species occurrence records (Chapman, 2005). Traditionally, the collection of georeferenced species observations has depended on heavy investment of time and resources in field surveys, and as such, species occurrence datasets are often very limited (Ahrends *et al.,* 2011; Rovero *et al.,* 2014). In addition, many existing datasets suffer inaccuracies due to misidentification of species (Beerkircher *et al.,* 2009; Shea *et al.,* 2011; Costa *et al.,* 2015), unaddressed changes in taxonomy (Tessarolo *et al.,* 2017), imprecise localities, erroneous conversion of coordinates between systems, and post hoc assignment of observations to the wrong locality (Maldonado *et al.,* 2015). Such errors effectively make the records with which they are associated false positives and distort our knowledge of species' true ranges (Maldonado *et al.,* 2015).

At least some of these issues are being mitigated through the development of techniques that can collect data far more rapidly than with the traditional field survey model. For example, the advent of citizen science now means that biodiversity data can be collected extremely rapidly and in vast volumes for some groups, potentially addressing data quantity issues in species occurrence datasets (Silvertown, 2009; Soroye *et al.,* 2018). In fact, millions of occurrence records are submitted to large scale citizen science projects every year (Sullivan *et al.,* 2014), dramatically increasing

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our ability to understand species occurrence and distributions (e.g., Fink *et al.,* 2013; Soroye *et al.,* 2018; Johnston *et al.,* 2021).

Knowledge of species' distributions is particularly poor for amphibians (Ficetola *et al.,* 2014; Loebmann *et al.,* 2017), which comprise the most highly threatened and poorly known terrestrial vertebrates globally (IUCN, 2021a). Amphibian occurrence data suffer issues with both quantity and quality because many species are difficult to detect (Rocha *et al.,* 2004; Hsu *et al.,* 2005; Heard *et al.,* 2006; Renan *et al.,* 2017) or identify (Donnellan *et al.,* 1999; Bickford *et al.,* 2007), particularly if not calling in the case of frogs (Rowley *et al.,* 2019). Amphibian taxonomy is highly dynamic, with many morphologically cryptic species complexes harbouring undiagnosed diversity (Rowley *et al.,* 2015), rendering many old records erroneous unless their taxonomy can be reliably updated (Ficetola *et al.,* 2014). In fact, more than 30% of high-quality species occurrence records from Oceania project outside their distribution map created for the Global Amphibian Assessment (GAA) in 2004 (Ficetola *et al.,* 2014). Despite this, the GAA maps are widely considered the best for amphibian distributions and are frequently used in conservation studies (Cooper *et al.,* 2008; Lawler *et al.,* 2010; Ficetola *et al.,* 2014), yet almost none have been updated for some regions on the IUCN Red List of Threatened Species since the GAA (IUCN, 2021b).

Citizen science has been successful in gathering many frog species occurrence records (iNaturalist, 2021; HerpMapper, 2021; QuestaGame, 2021). FrogID is an Australia-wide citizen science project run by the Australian Museum that aims to collect accurate, georeferenced presence data for Australian frogs. The mobile phone app-based project allows users to submit recordings of male frog advertisement calls from anywhere in Australia to build a database of frog localities (Rowley *et al.,* 2019). It is designed to collect and process observations in a way that mitigates the data quality issues inherent in many existing datasets, both citizen science and traditional. The FrogID app uses a phone's GPS capabilities to automatically assign coordinates to each record, with an estimate of location accuracy (Rowley *et al.,* 2019). The time and date of each recording are also automatically added, eliminating user error (Rowley *et al.,* 2019). The app relies on identifying male advertisement calls, which are less invasive to record and typically more reliable than photographs for identification of many species, and identifications are validated by at least one frog identification expert (Rowley *et al.,* 2019).

Since launching in 2017, FrogID has collected over 500,000 species observations (FrogID, 2021), and now represents the largest single occurrence dataset on Australia's frogs. We leveraged the recent, rapid increase in georeferenced observations of Australian frog species to estimate Australian frog species distributions and create the Australian Frog Atlas. We also present an updated map of frog species richness across Australia.

Methods

We obtained all validated FrogID records as of 12 January 2022, a total of 547,153 records of 209 species. These represent 52% of the volume of frog records from all sources in the national aggregate of species observations, the Atlas of Living Australia (ALA), which includes records back to the first collected specimens in 1754 (ALA, 2021).

We mapped the distribution of all 248 frog species known from Australia in ArcMap 10.7.1 (ESRI, California, USA). To inform species' distributions we projected FrogID data on the 2020 ESRI World Imagery basemap and referred to ALA records available using the interactive map function (ALA, 2021). We also used both text and maps from existing literature. Publishing precise localities of some species can inadvertently facilitate the illegal collection of individuals (Stuart *et al.,* 2006; Tann & Flemons, 2009) or disturbance of populations and habitat associated with wildlife enthusiasts and photographers searching for the species (Lindenmayer & Scheele, 2017; Tulloch *et al.,* 2018). Therefore, we followed Rowley & Callaghan (2020) in treating locality data of certain species as sensitive and mapped those species' distributions based on records generalized to the nearest 0.1 decimal degrees.

We characterized the broad habitat types with which species are associated by consulting literature, our own field observations, and by assessing the position of most observations relative to habitat types discernible from satellite imagery. We deemed FrogID and ALA records that had estimates of spatial uncertainty of 3 km or higher as spatially suspect and did not use them to inform species' habitat requirements or range boundaries if they were also outside the habitat types that most other records projected in, or if they appeared to be geographic outliers.

Once habitats were assessed, we created layer files for each species and drew polygons, tracing finely around contiguous areas that contained both reliable records and suitable habitat. We mapped species that are now extinct or have undergone range reductions according to their historic distribution, except where suitable habitat has been removed and the species is unlikely to occur in the modified habitat (for example, previously forested areas where forest-dependant species once occurred). We included areas where species appear to have been extirpated by enigmatic processes or disease, but which retain intact suitable habitat, and thus could potentially harbour undetected populations or be recolonized post-recovery.

We determined how far from records to extend polygons into contiguous habitat by a combination of the geographic spread and number of records, the relative position of potential barriers to dispersal (i.e. large geological features), and the likely relative sampling effort across the area. Factors that encouraged extrapolation were: expansive suitable habitat contiguous with records, relatively few records across a relatively large geographic spread, apparent absence of nearby barriers, and low perceived sampling effort in the area. The inverse of these discouraged extrapolation. The extension of polygons into contiguous habitat ranged from approximately 1–20% of the area of a convex hull of actual observations. We removed areas contained within inhabited polygons that are unlikely to be inhabited by the species, and then smoothed polygons with a smoothing tolerance of 2–10 km.

We downloaded the Interim Biogeographic Regionalisation for Australia (IBRA) shapefile (DAWE, 2021) and created a version that excluded small islands, leaving only mainland Australia and Tasmania. We clipped polygons to the modified IBRA shapefile to restrict them to land areas and maintain a consistent coastline among species' maps. When species also occurred on islands, we either hand-traced inhabited islands or drew polygons over them and then clipped those polygons to the original shapefile.

We did not map the distributions of *Litoria barringtonensis*, *L. nudidigitus*, *L. pearsoniana*, *L. phyllochroa*, and *L. kroombitensis* during this study. For those species we had created detailed distribution maps previously using methods outlined in Cutajar & Rowley (2022, in press), and so we checked these existing maps against this study's dataset and included them in the Atlas.

We converted the outputs of the mapping process to shapefiles. We also used the *rmapshaper* (Teucher & Russell, 2021) and *rgdal* (Bivand *et al*., 2021) packages in R (R Core Team, 2021) to make very slightly simplified KML (*Keyhole Markup Language* for expressing maps in Google Earth) versions of the shapefiles. To increase the usability of shapefiles for future analyses, we named each shapefile according to a "Genus_species" format. We also added a field titled "Species" to each shapefile's attributes table and populated its cells with the species' name. To visualize frog species richness across Australia, we overlaid the new distributions of every species, producing a country-wide heat map in ArcMap 10.7.1 comprised of a mosaic of polygons, each containing a value for the number of species' distributions that overlap at their given location.

Results

We produced shapefiles and KML files of distribution maps for all 247 currently recognized native frog species in Australia, and the invasive Cane Toad (*Rhinella marina*). A map of each species' distribution is presented in the appendix. We also produced a shapefile and map of frog species richness across the Australian continent (Fig. 1). The polygons that comprise the species richness mosaic varied in size from < 0.0001 to 292,045 km^2, with a mean and median of 232 and 0.77 km^2, respectively. The datum for all spatial resources is WGS 84. All files (individual species' distributions and species richness) are freely available as an Open Access resource published by us separately under Creative Commons (CC BY 4.0) in a self-hosted *Zenodo* repository (Cutajar *et al*., 2021). As more data become available we intend, perhaps annually, to revise maps. The DOI for the resource (see Cutajar *et al*., 2021 = https://doi.org/10.5281/zenodo.6544829) will always direct users to the most up-to-date version of distribution files.

Based on our current knowledge of species richness (Fig. 1), the Wet Tropics of Queensland (QLD) is the most species-rich area of Australia, where the ranges of 45 species overlap in small areas near Mt Lewis National Park and Baldy Mountain Forest Reserve. The next most species-rich areas, with sections of varying size potentially supporting 41 and 40 species, are the montane eastern border area of QLD and New South Wales (NSW) and the Southern Ourimbah—Central Coast area about 50 km north of the Sydney CBD, respectively. The areas around Dorrigo and Washpool National Parks, NSW, follow at 39 species. These hyper-rich areas are fragments of a continuous band of relatively high richness along eastern Australia approximately between Gladstone, QLD and Jervis Bay, NSW. Other areas, in descending order of their most speciose polygons, are the border of Western Australia (WA) and the Northern Territory (NT) north of Lake Argyle (31 species), the Kimberly in WA either side of Prince Regent River, and forested areas of the Darling Downs region (QLD) (30 species).

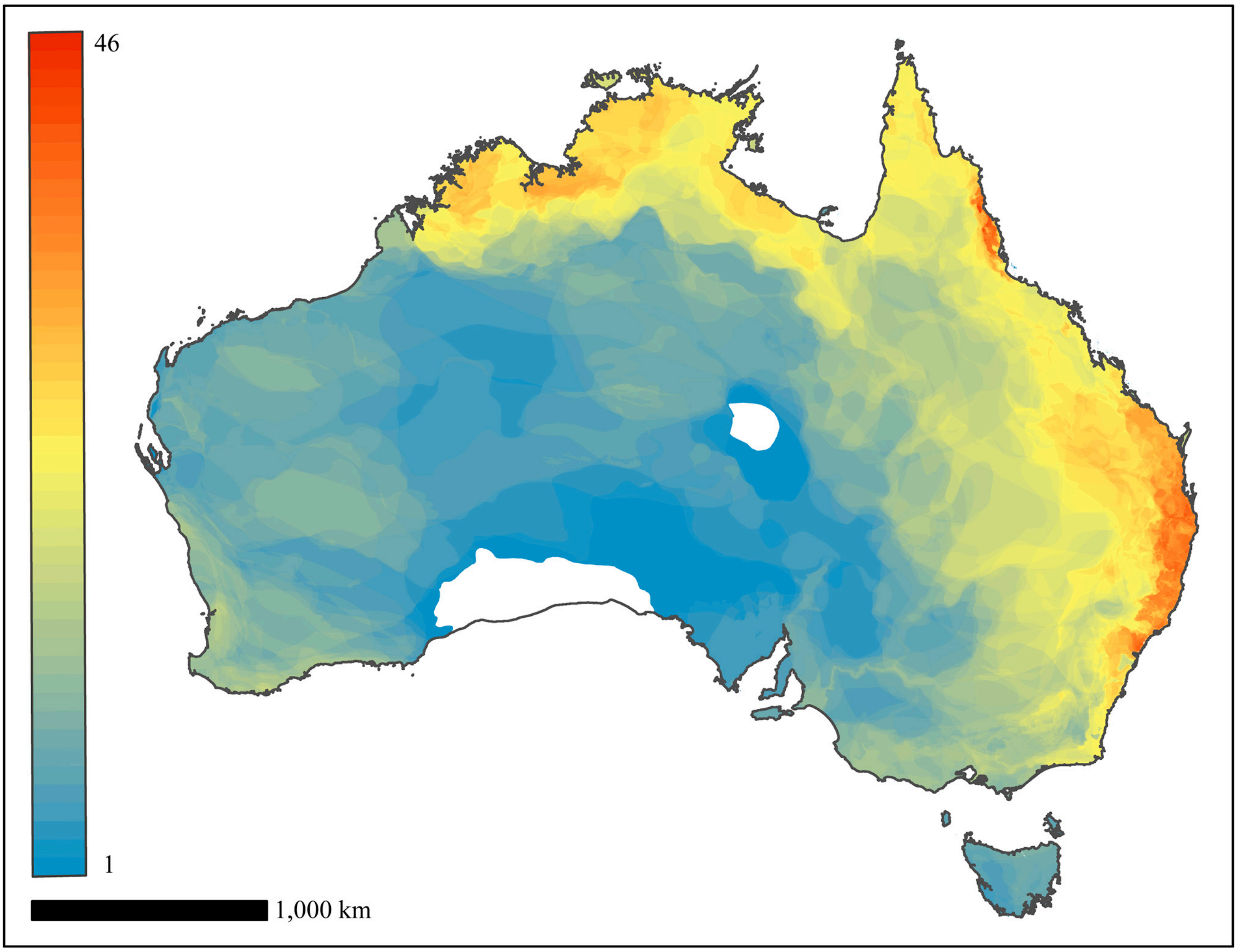

Figure 1. Map of Australia showing our current understanding of amphibian species richness based on overlaid Australian Frog Atlas species distributions. Colour ramp indicates the number of co-occurring frog species from one (blue) to 45 (red). White spaces represent areas where no frogs are known.

Discussion

The Australian Frog Atlas is the most up-to-date and comprehensive resource for distribution maps of Australia's frog fauna. Its maps include recent range extensions discovered via citizen science for multiple species. For example, through submissions to FrogID, the known range of the striped rocket frog (*Litoria nasuta*) was extended approximately 180 km southeast into Gregory National Park, NT, and the range of the crucifix frog (*Notaden bennettii*) was extended west at two separate points by 100 km and 172 km. In addition to extensions, vetting of existing data resulted in considerable changes to other species' ranges. For example, Sloane's froglet (*Crinia sloanei*) has historical records spanning almost 1,000 km from Queensland to Victoria and existing maps for multiple conservation assessments reflect these (Hero *et al.,* 2004; OEH, 2021). However, many records are thought to be misidentifications and the species is only known with certainty south of Dubbo, NSW (Spark, 2015; Threatened Species Committee, 2019). This results in the species' estimated range likely being approximately half that previously estimated, with implications for its conservation status (Threatened Species Committee, 2019).

Our maps allow a relatively fine-scale estimate of how frog species richness is distributed across Australia. Past studies of Australian frog species richness have typically used coarse polygons as input or presented results as a low-resolution (10–55 km^2) gridded map (Slatyer *et al.,* 2007; Chanson *et al.,* 2008; Cogger, 2018). We analysed species richness based on very detailed distribution maps. Our results are presented as a high-resolution mosaic of polygons that, based on those maps, each represent an area throughout which the same species assemblage can be expected, and that vary in size with a median of 0.77 km^2. We found the location with the highest species richness (45 species) within the Wet Tropics, QLD, approximately between Cairns and the Daintree River, where Slatyer *et al.* (2007) and Cogger (2018) also reported the highest richness at 45 and 49 species, respectively. The differences in the values given here and in Cogger (2018) are presumably due to the previous use of large grid cells, versus fine-scale polygons in this study.

In addition to hotspots, the utility of species richness maps to indicate "cold spots", where species richness is likely to have been artificially reduced by threatening processes like land clearing, was pointed out by Cogger (2018). The map in this study appears to demonstrate two such areas in NSW, where species richness is low relative to surrounding areas of comparable elevation, but where natural forest has been removed: the Sydney basin and west of Bega. This map also shows two areas where apparently no frog species occur: the Nullarbor Plain spanning south-eastern WA and south-western South Australia, and approximately 27,000 km^2 of the Simpson Desert in the NT. The absence of frogs in much of the Nullarbor Plain is supported by other work (e.g., Cogger, 2018), however the gap in the Simpson Desert is, to our knowledge, undocumented. There are no records in the ALA or FrogID datasets of any frog species from the area. It is possible that this is due to limited access for surveys rather than a true lack of frogs, however there are numerous ALA records from the area of reptiles (ALA, 2021), which are often collected together with frogs (e.g., Dell & Chapman, 1979; Vanderduys *et al.,* 2011).

The use of presence only data, both from citizen science and traditional sources, in delineating species' ranges inevitably introduces certain biases, including a spatial bias towards populated areas (Boakes *et al.,* 2010; Aceves-Bueno *et al.,* 2017; Cogger, 2018). As such, both inter- and intraspecific inconsistencies in the accuracy of range boundaries across space should be expected, highlighting the need for increased survey efforts for poorly known species and those in remote areas (Callaghan *et al.,* 2019; Callaghan *et al.,* 2020). Another cause of interspecific inconsistency in the precision and accuracy of species' distribution maps is following forest edges adjacent to records using satellite imagery; it was much easier to estimate the limits of forest-dependant species than those of habitat generalists. Increased engagement of landholders with citizen science could potentially mitigate this by augmenting data from privately held, more modified areas, where the boundaries of some generalist species may lie.

While all 247 native frog species and the introduced Cane Toad (*Rhinella marina*) were mapped for this project, some species are presumed extinct (Skerratt *et al.,* 2007), and others have been locally extirpated in parts of their historic range (Hunter *et al.,* 2018). In these cases, our maps are representative of species' historic distributions, including where species are no longer found but where suitable habitat remains and species could recolonize. The maps provided here include only species' ranges within Australia, despite 16 Australian frog species also being native to Papua New Guinea and others having been introduced to other parts of Oceania (Cogger, 2018). In cases where Australian frog species have established breeding populations outside their native range but within Australia (e.g., *Litoria fallax*; Rowley *et al.,* 2019), we included these new populations in species' maps.

Our intention is that these maps assist with informing conservation of Australia's frogs, many of which are threatened, and we have made shapefiles and KML files of each individual species' map and a shapefile of the species richness map freely available for download. We intend that they be used by researchers and conservation practitioners for understanding the ecology, behaviour and conservation of Australia's frogs, as have earlier unpublished versions (Rowley *et al.,* 2019; Mitchell *et al.,* 2020; Weaver *et al.,* 2020), but they are available for any non-commercial use. The species richness and individual species distributions may help inform analyses of species endemism or biogeography, or to determine the coverage of protected areas relative to the distribution of threatened species, and even identify priority areas for habitat protection. We intend to update these files on an approximately annual basis.

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Appendix

Appendix. [See pages 7–48]. Distribution maps of all 248 frog species known from Australia. Distributions outside Australia of non-endemic species are not shown. Green circles indicate the location of very range-restricted species.

Adelotus brevis

Arenophryne rotunda

Arenophryne xiphorhyncha

Assa darlingtoni

Assa wollumbin

Austrochaperina adelphe

Austrochaperina fryi

Austrochaperina gracilipes

Austrochaperina pluvialis

Austrochaperina robusta

Cophixalus aenigma

Cophixalus australis

Cophixalus bombiens

Cophixalus concinnus

Cophixalus crepitans

Cophixalus exiguus

Cophixalus hinchinbrookensis

Cophixalus hosmeri

Cophixalus infacetus

Cophixalus kulakula

Cophixalus mcdonaldi

Cophixalus monticola

Cophixalus neglectus

Cophixalus ornatus

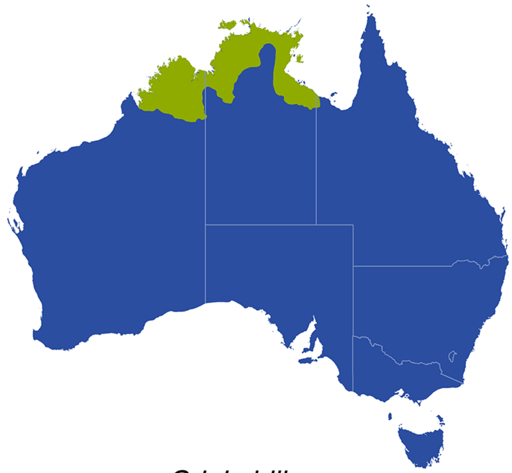
Cophixalus pakayakulangun

Cophixalus peninsularis

Cophixalus petrophilus

Cophixalus saxatilis

Cophixalus zweifeli



Crinia bilingua

Crinia deserticola

Crinia fimbriata

Crinia flindersensis

Crinia georgiana

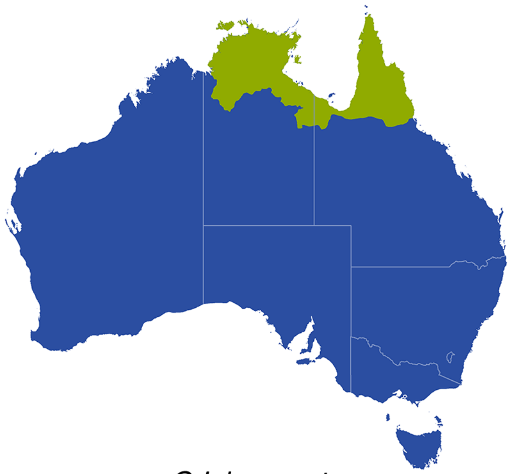
Crinia glauerti

Crinia insignifera

Crinia nimbus

Crinia parinsignifera

Crinia pseudinsignifera



Crinia remota

Crinia riparia

Crinia signifera

Crinia sloanei

Crinia subinsignifera

Crinia tasmaniensis

Crinia tinnula

Cyclorana alboguttata

Cyclorana australis

Cyclorana brevipes

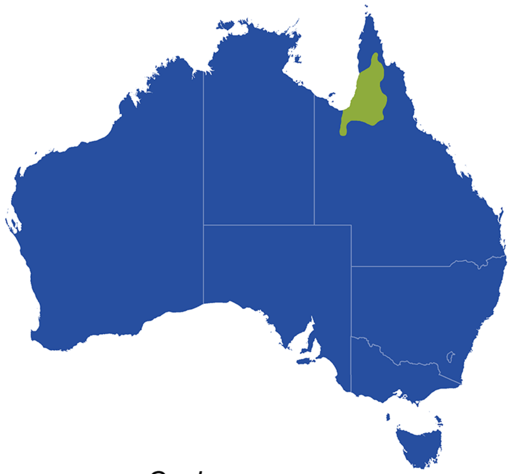
Cyclorana cryptotis

Cyclorana cultripes

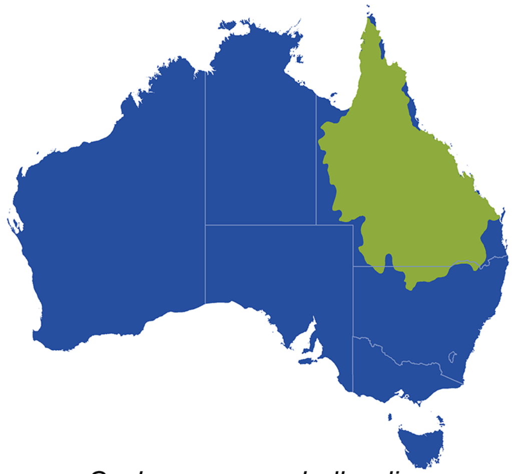
Cyclorana longipes

Cyclorana maculosa

Cyclorana maini



Cyclorana manya



Cyclorana novaehollandiae

Cyclorana occidentalis

Cyclorana platycephala

Cyclorana vagitus

Cyclorana verrucosa

Geocrinia alba

Geocrinia laevis

Geocrinia leai

Geocrinia lutea

Geocrinia rosea

Geocrinia victoriana

Geocrinia vitellina

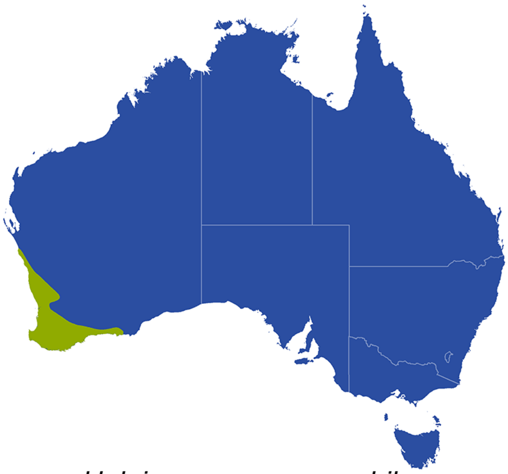
Heleioporus albopunctatus

Heleioporus australiacus

Heleioporus barycragus

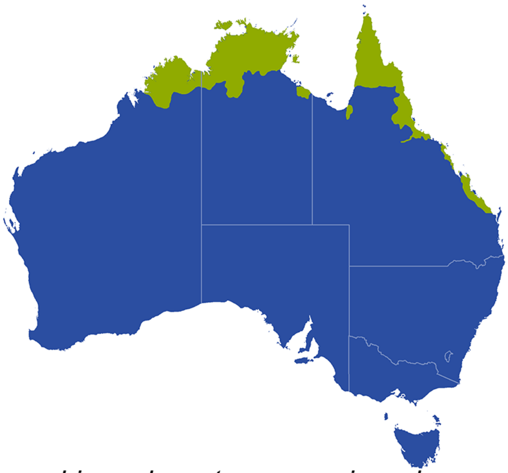
Heleioporus eyrei

Heleioporus inornatus



Heleioporus psammophilus

Lechriodus fletcheri



Limnodynastes convexiusculus

Limnodynastes depressus

Limnodynastes dorsalis

Limnodynastes dumerilii

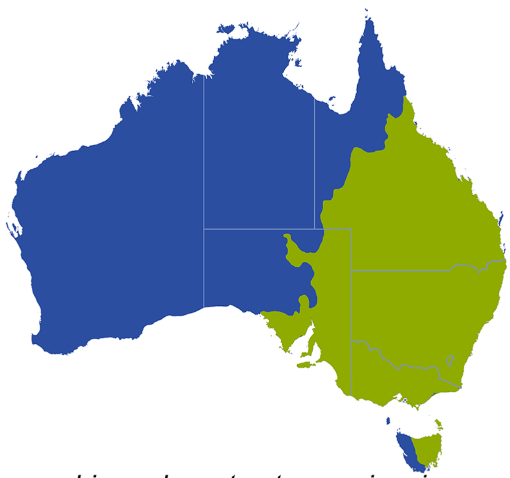
Limnodynastes fletcheri

Limnodynastes interioris

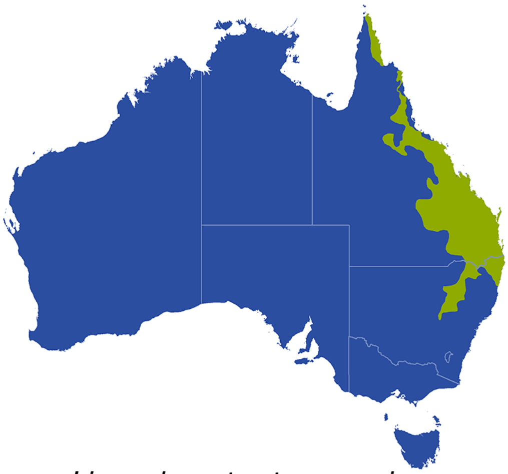
Limnodynastes lignarius

Limnodynastes peronii

Limnodynastes salmini



Limnodynastes tasmaniensis



Limnodynastes terraereginae

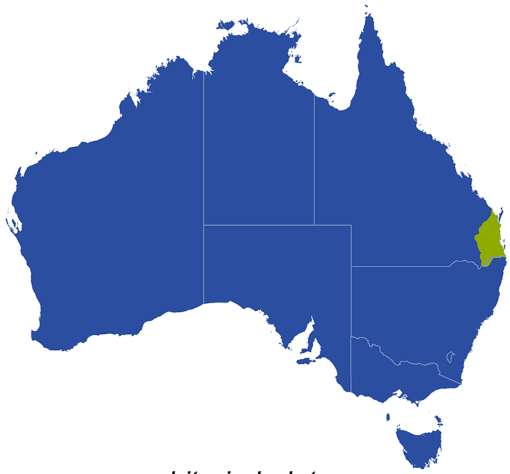
Litoria adelaidensis

Litoria andiirrmalin

Litoria aurea

Litoria aurifera

Litoria axillaris



Litoria balatus

Litoria barringtonensis

Litoria bella

Litoria bicolor

Litoria booroolongensis

Litoria brevipalmata

Litoria burrowsae

Litoria caerulea

Litoria castanea

Litoria cavernicola

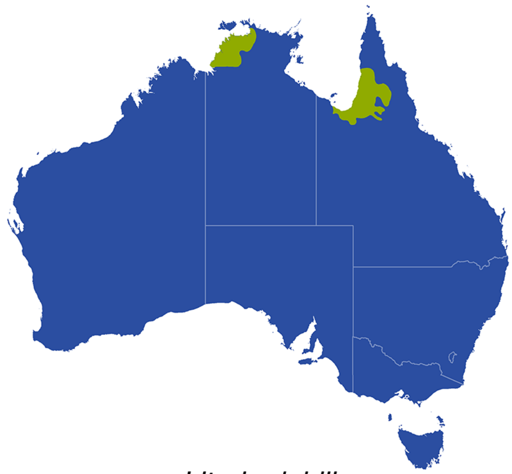
Litoria chloris

Litoria citropa

Litoria cooloolensis

Litoria coplandi

Litoria cyclorhyncha

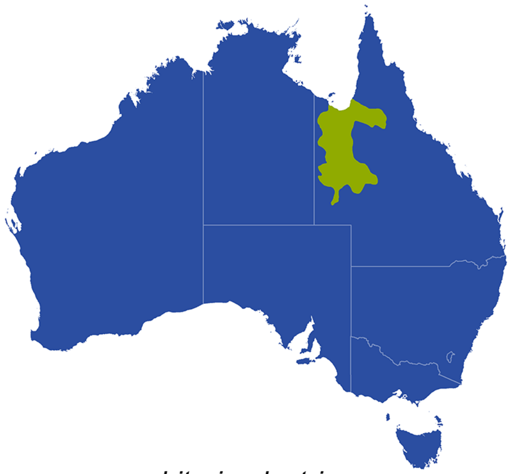


Litoria dahlii

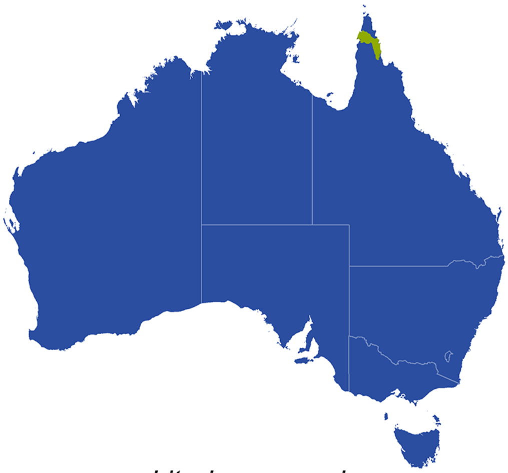
Litoria daviesae

Litoria dayi

Litoria dentata



Litoria electrica



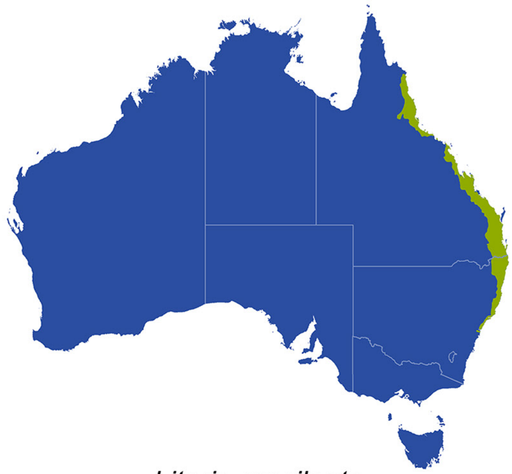
Litoria eucnemis

Litoria ewingii

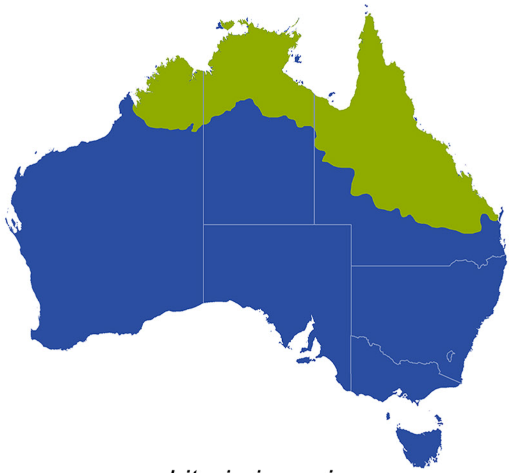
Litoria fallax

Litoria freycineti

Litoria gilleni



Litoria gracilenta



Litoria inermis

Litoria infrafrenata

Litoria jervisiensis

Litoria jungguy

Litoria kroombitensis

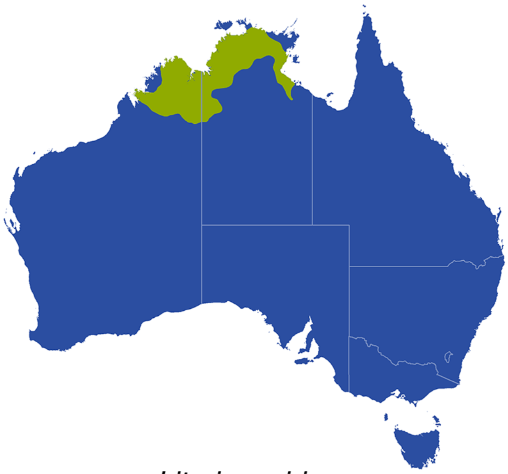
Litoria latopalmata

Litoria lesueuri

Litoria littlejohni

Litoria longirostris

Litoria lorica



Litoria meiriana

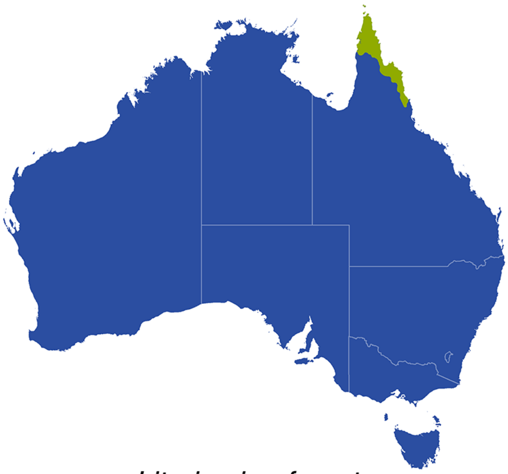
Litoria microbelos

Litoria moorei

Litoria myola

Litoria nannotis

Litoria nasuta

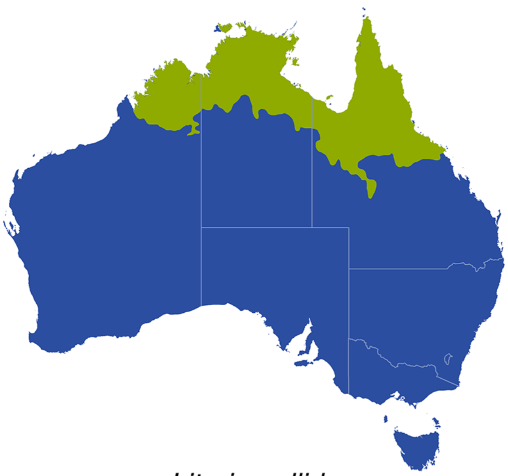


Litoria nigrofrenata

Litoria nudidigitus

Litoria nyakalensis

Litoria olongburensis

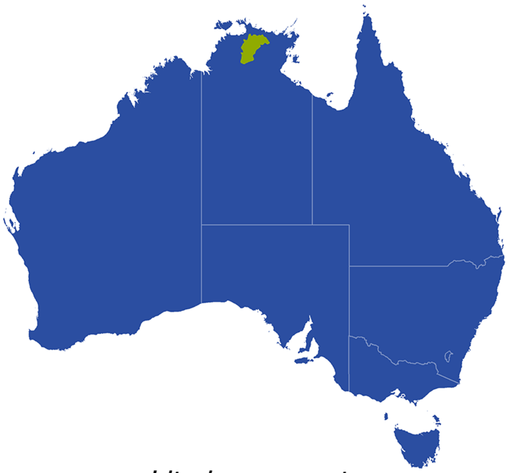


Litoria pallida

Litoria paraewingi

Litoria pearsoniana

Litoria peronii



Litoria personata

Litoria phyllochroa

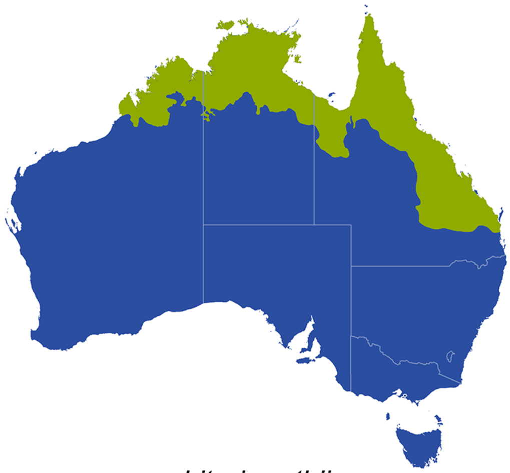
Litoria piperata

Litoria quiritatus

Litoria raniformis

Litoria revelata

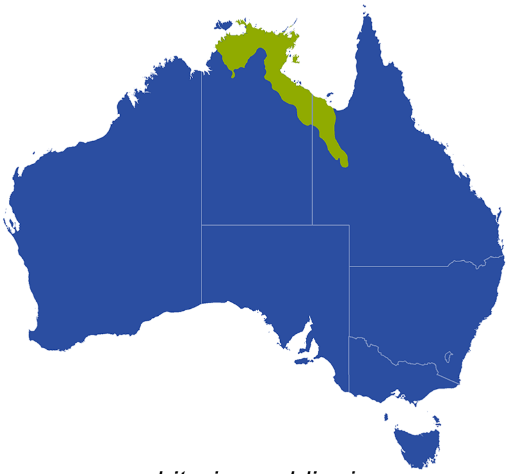
Litoria rheocola



Litoria rothii

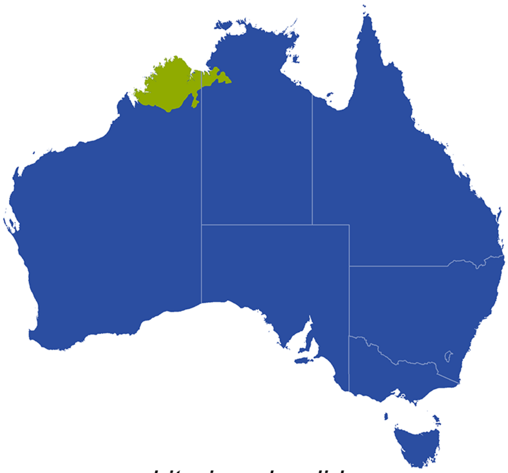
Litoria rubella

Litoria serrata

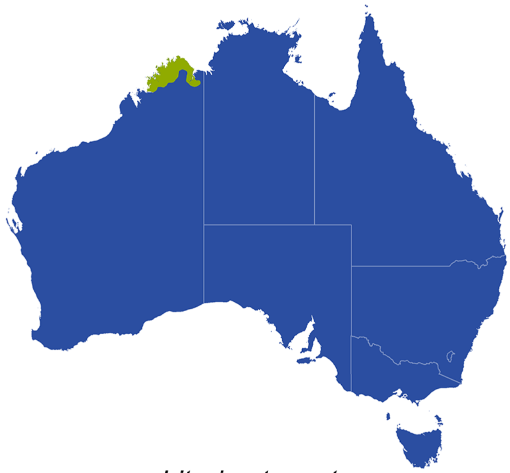


Litoria spaldingi

Litoria spenceri

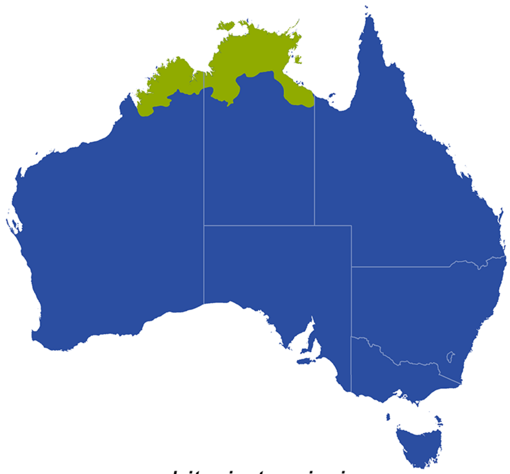


Litoria splendida



Litoria staccato

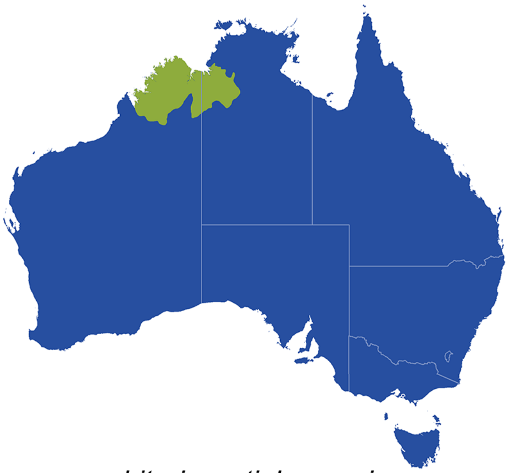
Litoria subglandulosa



Litoria tornieri

Litoria tyleri

Litoria verreauxii



Litoria watjulumensis

Litoria watsoni

Litoria wilcoxii

Litoria xanthomera

Metacrinia nichollsi

Mixophyes balbus

Mixophyes carbinensis

Mixophyes coggeri

Mixophyes fasciolatus

Mixophyes fleayi

Mixophyes iteratus

Mixophyes schevilli

Myobatrachus gouldii

Neobatrachus albipes

Neobatrachus aquilonius

Neobatrachus fulvus

Neobatrachus kunapalari

Neobatrachus pelobatoides

Neobatrachus pictus

Neobatrachus sudellae

Neobatrachus sutor

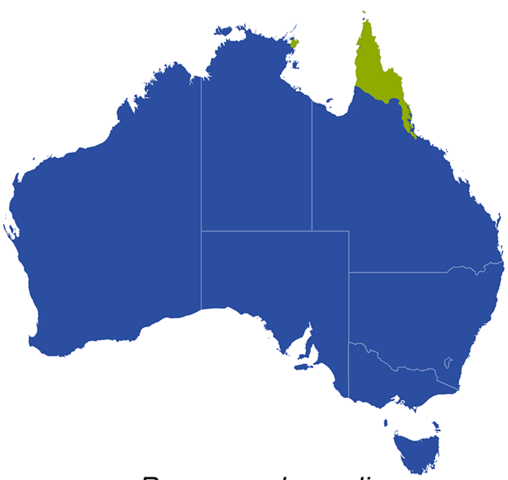
Neobatrachus wilsmorei

Notaden bennettii

Notaden melanoscaphus

Notaden nichollsi

Notaden weigeli



Papurana daemeli

Paracrinia haswelli

Philoria frosti

Philoria knowlesi

Philoria kundagungan

Philoria loveridgei

Philoria pughi

Philoria richmondensis

Philoria sphagnicola

Platyplectrum ornatum

Platyplectrum spenceri

Pseudophryne australis

Pseudophryne bibronii

Pseudophryne coriacea

Pseudophryne corroboree

Pseudophryne covacevichae

Pseudophryne dendyi

Pseudophryne douglasi

Pseudophryne guentheri

Pseudophryne major

Pseudophryne occidentalis

Pseudophryne pengilleyi

Pseudophryne raveni

Pseudophryne robinsoni

Pseudophryne semimarmorata

Rheobatrachus silus

Rheobatrachus vitellinus

Rhinella marina

Spicospina flammocaerulea

Taudactylus acutirostris

Taudactylus diurnus

Taudactylus eungellensis

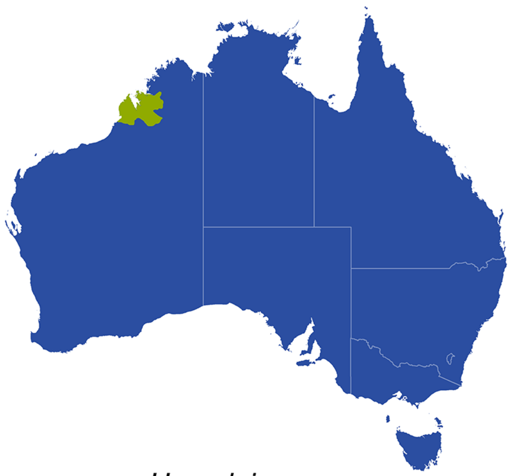
Taudactylus liemi

Taudactylus pleione

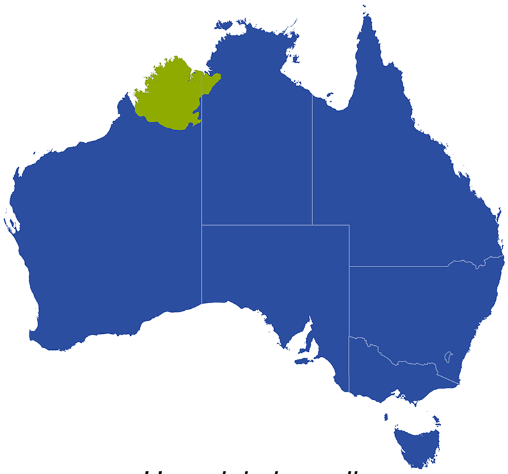
Taudactylus rheophilus

Uperoleia altissima

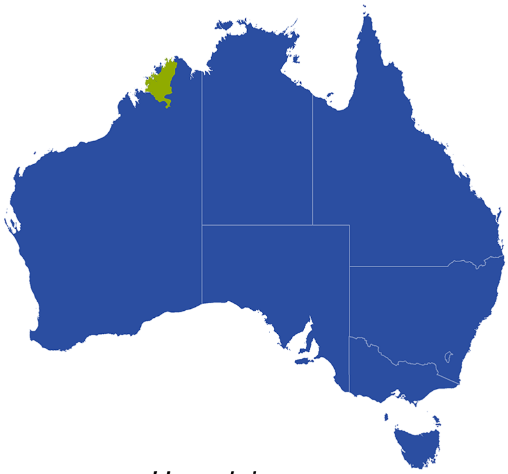
Uperoleia arenicola



Uperoleia aspera

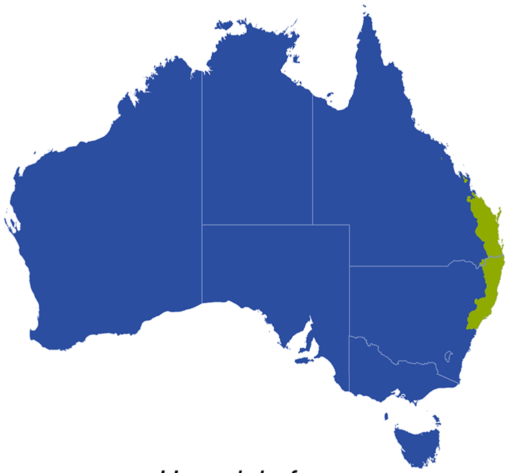


Uperoleia borealis



Uperoleia crassa

Uperoleia daviesae



Uperoleia fusca

Uperoleia glandulosa

Uperoleia gurrumuli

Uperoleia inundata

Uperoleia laevigata

Uperoleia lithomoda

Uperoleia littlejohni

Uperoleia mahonyi

Uperoleia marmorata

Uperoleia martini

Uperoleia micra

Uperoleia micromeles

Uperoleia mimula

Uperoleia minima

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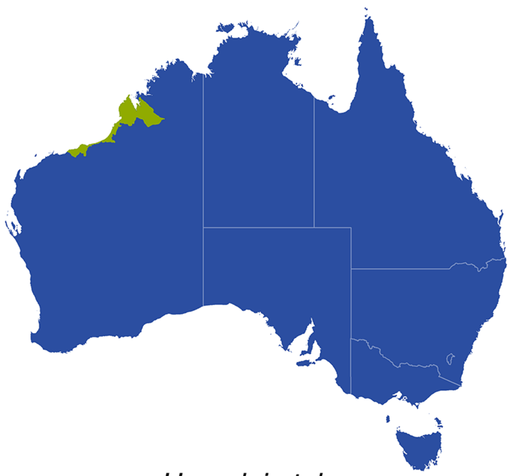
Uperoleia rugosa

Uperoleia russelli

Uperoleia saxatilis

Uperoleia stridera



Uperoleia talpa

Uperoleia trachyderma

Uperoleia tyleri