Threatened Species Recovery Hub

National **Environmental Science** Programme

A prioritisation of threatened species monitoring in Australia

Final Report

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Cover image: The short-nosed sand plover (Charadrius mongolus). *Image: Imran Shah, CC BY-SA 2.0, Flickr*

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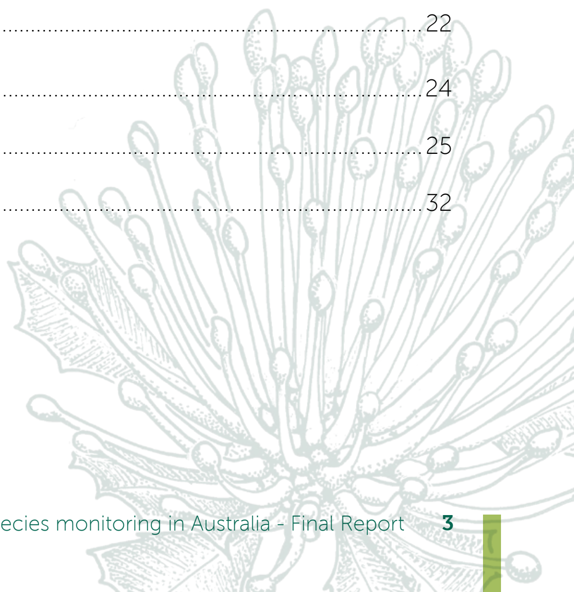


Executive summary

Biodiversity monitoring is crucial to understanding the status, distribution and trends in threatened species. With an increasing species extinction crisis, better methods are needed to design biodiversity monitoring programs and prioritise investment when conservation resources are limited. In this report, we developed a decision-theoretic framework for prioritising investment in threatened species monitoring while explicitly accounting for extinction risk, surrogacy, statistical power and monitoring cost. We applied our framework to prioritise and estimate the total cost of monitoring 1828 threatened species in Australia. Specifically, we 1) compiled national databases on traits, survey methods, and sampling effort for threatened species; 2) quantified extinction risk based on intrinsic ecological traits; 3) estimated the surrogacy potential of species given threats, ecology, habitat requirements and geographic range, and; 4) estimated the indicative cost of detecting trends in species given preferred sampling methods, detectability and opportunities to detect multiple species with single sampling methods. We estimated that monitoring all of Australia's EPBC listed species so that we can detect small-to-moderate declines with high (80%) power, will cost AUD $179 – 307 million per year depending on the extent of cost sharing. Our prioritised list of species to be monitored was dominated by plants.

Introduction

The extinction of species around the world is one of the most pressing environmental challenges facing humanity (Ceballos et al. 2017). Global rates of extinction are now two to three orders of magnitude greater than background levels recorded in geological history (De Vos et al. 2015) due to accelerated habitat destruction, overexploitation, spread of invasive species, disease and global expansion of the human population. Understanding the status, distribution and trends of species most vulnerable to extinction is crucial to implementing effective conservation actions (Whittaker et al. 2005, Boitani et al. 2011, Pino-Del-Carpio et al. 2014). General biodiversity inventories (Lawton et al. 1998, Richards and Whitmore 2015), targeted species surveys (Dempsey et al. 2014) and ongoing monitoring of biodiversity is needed to improve knowledge of where species are located in the landscape and how they are trending over time. With an increasing species extinction crisis, better methods are needed to design biodiversity monitoring programs (Waldron et al. 2017) and prioritise investment when conservation resources are limited.

Decisions about where, what and how to monitor should consider survey costs (Grantham et al. 2008). Given the time and equipment needed for field surveys and the remoteness of some species, substantial funds may be required to assess the status and trends of threatened species. Some species will be more expensive to monitor than others; for example, those found in remote locations or those needing specialised equipment of expert personnel for detection. Monitoring cost is also influenced substantially by the number of sites. Populations vary naturally across space and time and monitoring should be designed with a sufficient number of sites to ensure a high level of statistical power. An increasing body of research now focuses on assessing the costs and effectiveness of different approaches to surveying and monitoring biodiversity. This includes incorporating costs into survey design (Loyola et al. 2009), guidelines on the number of sites needed to detect change, identifying cost-effective survey methods for different taxa (Garden et al. 2007), optimizing ecological survey effort when species detection is uncertain (Moore et al. 2014), and prioritizing survey locations (Tulloch et al. 2013a, Carvalho et al. 2016).

In addition to cost, many governments, conservation agencies and scientists are using umbrella prioritisation approaches and/or identifying surrogate species to improve cost-efficiency of monitoring and management. In the context of threatened species monitoring, surrogacy assumes that tracking trends of one species provides information on other species that are not detected, but are expected to respond to changes in the environment in the same way, such as in the presence of threats. Prioritising monitoring towards surrogates may therefore provide the most useful information at the least cost, especially when target species are cryptic or expensive to monitor. Recent efforts to prioritise threatened species monitoring and management have focused on complementarity and surrogacy (e.g., (Justus and Sarkar 2002, Rodrigues and Brooks 2007); management effectiveness (Walsh et al. 2012); species weightings (Joseph et al. 2009) or species detectability.

There is an extensive body of literature predicting extinction risk of species based on intrinsic and extrinsic ecological traits; however, there are few examples where extinction risk studies have informed allocation of monitoring resources. Further, to our knowledge, no attempt has been made to estimate monitoring cost and prioritise data acquisition efforts for threatened species at a continental scale. Efforts to incorporate surrogacy into monitoring prioritisation decisions have also generally focused on small sets of species across small spatial scales. There is a need for general frameworks to assess the relative costs and benefits of monitoring species at landscape scales, combined with optimisation approaches, to improve transparent and more efficient allocation of resources while minimising the risk of extinction. Decision makers need a repeatable and systematic way to select a set of indicator species to monitor, to ensure changes are detected when they occur, and to reduce the chance of species extinction. Assessing the relative costs and benefits of monitoring species, combined with optimisation approaches, can lead to a transparent and more efficient allocation of resources while maximising conservation gains (Ward et al. 2020).

In this report, we developed a decision-theoretic framework for prioritising investment in threatened species monitoring while explicitly accounting for extinction risk, surrogacy, statistical power and monitoring cost. We applied our framework to prioritise and estimate the total cost of monitoring 1828 threatened species in Australia. Australia provides a good case study because it has one of the highest rates of extinction in the world (Woinarski et al. 2011), with at least three species having gone extinct in the last decade (Woinarski et al. 2017a). The paucity of monitoring information and programs for threatened species in Australia has long been recognised as an impediment to recovery; however, the status of monitoring has not advanced substantially in recent decades. A recent study found that 21% - 46% of threatened vertebrates receive no monitoring at all, and monitoring programs that do exist are generally inadequate (Scheele et al. 2019). Even fewer threatened plants and invertebrates have ongoing and well-designed monitoring programs, which means the status and trends of the majority of Australia's threatened species is not known (Lavery et al. 2021).

Using real time series data to characterise population variability over time, we developed a transparent and repeatable framework for estimating the cost of monitoring species and selecting a complementary set of indicator species with the aim of minimising the number of species at risk of extinction. Specifically, to prioritise monitoring for threatened species in Australia we: 1) reviewed the scientific and grey literature to compile a national database on traits, survey methods, and sampling effort for threatened species; 2) quantified extinction risk for species based on intrinsic ecological traits; 3) estimated the ability of species to act as surrogates for others given threats, ecology, habitat requirements and geographic range, and; 4) estimated the indicative cost of detecting trends in species given preferred sampling methods, detectability and opportunities to detect multiple species with single sampling methods. Using these approaches, we estimated how much it will cost to monitoring all of Australia's threatened species with a high level of statistical power to detect small-moderate changes in populations and found the set of species that minimised the extinction risk over a range of fixed budgets.

*The Wet Tropics subspecies of the yellow-bellied glider (*Petaurus australis*) was one of the top 30 ranked EPBC listed species that are yet to be monitored with cost sharing. Image: David Cook, CC BY-NC 2.0, Flickr*

Methodology

Prioritisation approach

Our approach to costing and ranking threatened species for monitoring consisted of 7 steps: 1) define monitoring objectives and constraints: 2) list candidate species; 3) predict extinction risk using intrinsic ecological trait data; 4) determine surrogacy value; 5) calculate indicative monitoring costs to achieve a high level of statistical power; 6) combine information on extinction risk and surrogacy value to calculate monitoring benefits, and; 7) rank species by their cost-benefit while accounting for cost-efficiencies and monitoring programs already underway. A diagram of our approach is provided in Figure 1.

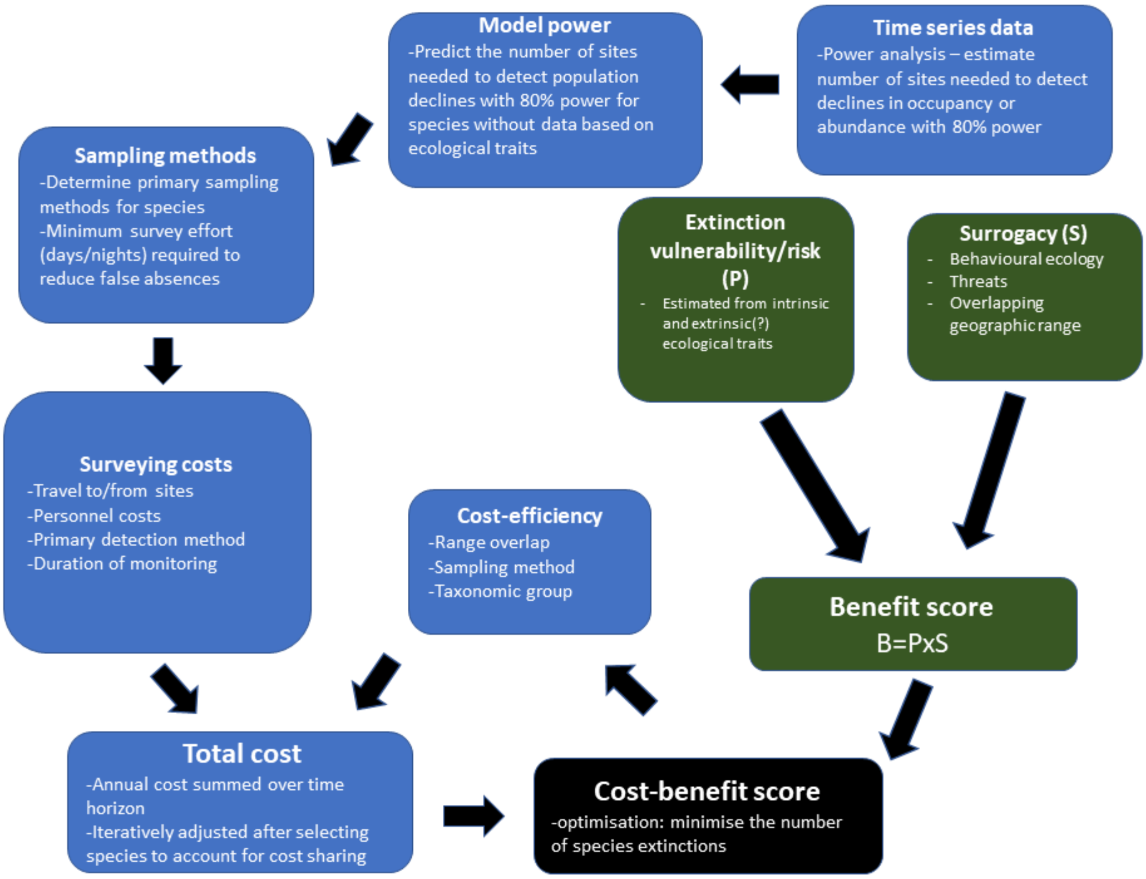


Figure 1: *The approach to prioritising monitoring for EPBC listed threatened species in Australia. Blue boxes represent the steps to estimating monitoring costs while the green boxes show how benefit scores are calculated.*

Defining objectives and constraints

To optimally allocate resources among monitoring projects, it is important to clearly define the monitoring objectives and constraints. Here, our objective is to select the best set of threatened indicator species to monitor that will minimise the expected risk of extinction. An important but different type of monitoring is to assess the effectiveness of management actions. We did not assess this type of monitoring nor did we consider the value or cost of management. Rather, we assumed monitoring is conducted primarily to understand the status, extent and trends of threatened species and that is information triggers timely and effective management responses that will reduce the risk of extinction.

List of candidate species

Australia has 1893 taxa (as of July 2019) listed as extinct or threatened with extinction under the *Environment Protection and Biodiversity Conservation Act 1999 (Commonwealth of Australia 1999)*. Plants make up the majority of the list (1374), followed by birds (156), mammals (134), invertebrates (66), reptiles (63), fishes (59), and amphibians (41). We considered all species on this list, except for marine mammals, seabirds, reptiles and fishes that require shipboard surveys conducted outside of continental Australia.

Extinction risk

We modelled extinction risk (also referred to as extinction proneness or vulnerability) for species using intrinsic ecological trait data (Chichorro et al. 2019). Links between traits and extinction risk have been discovered for mammals (Davidson et al. 2012, Capellini et al. 2015), amphibians (Cooper et al. 2008, Murray et al. 2011, Rago et al. 2012), birds (Blackburn et al. 2009), reptiles (Reed and Shine 2002), fishes (Olden et al. 2007, Santos et al. 2021), arthropods (Wong et al. 2019) invertebrates (Bland 2017) and to a lesser extent, plants (Darrah et al. 2017).

We collated trait data from published scientific papers, online databases, commonwealth listing and conservation advices, approved and draft species recovery plans, approved threat-abatement plans and species profiles. A list of traits collated by taxonomic group is provided in Table 1. Geographic range size is known to be a good predictor of extinction risk for many taxa. For extant species, we obtained range maps from the Australian Government's Species of National Environmental Significance (SNES) Database and only used "known' and 'likely' ranges in our analysis. These distributional data have been applied to many international studies (Guisan et al. 2013, Auerbach et al. 2015, Polak et al. 2016).

Table 1: *Intrinsic ecological traits collated for EPBC listed species and primary data sources.*

Group	Intrinsic traits	Primary data source
Birds	Range size, body mass, clutch size, generation length	(Garnett et al. 2015) (Woinarski et al. 2017b)
Mammals	Range size, body mass, Aquatic (yes, no), Activity (night or day), saxicoline (yes, no), ground foraging (always, never, sometimes)	(Woolley et al. 2019)
Amphibians	Range size, body size (snout-vent length), habitat (fossorial, terrestrial, aquatic, arboreal), activity (diurnal, nocturnal, crepuscular), litter size, direct development, larval stages	(Murray et al. 2011) (Oliveira et al. 2017)
Reptiles	Range size, body size (snout-vent length), Leg development (limbless, leg-reduced, four-legged, Hindlimbs only), Activity time (1=Nocturnal, 2=Diurnal, 3=Cathemeral), habitat (Terrestrial, arboreal, fossorial, saxicolous, aquatic), diet (Carnivorous, Omnivorous, Herbivorous), reproductive mode (Oviparous, Viviparous), clutch size.	(Cabrelli et al. 2014) (Meiri 2018)
Plants	Range size, plant growth form (e.g. shrub, subshrub, tree, prostrate), height, life history (perennial, annual, short-lived perennial), fruit type (e.g. legume, dehiscent, fleshy)	(Falster et al 2021)
Fish	Range size, water type (freshwater, saltwater), length, type of length (standard length, fork length)	(Boettiger et al. 2012)
Invertebrates	Microhabitat (deep burrow, shallow burrow, under rock, in soil, under logs, under bark, ground living, leaf litter on ground, elevated leaf litter, vegetation, standing wood, trees/shrubs, creeks/water)	Marsh (pers com)

Dealing with missing data

Despite our extensive literature review, we could not find trait data for all species. If the proportion of missing values was small for a trait (i.e. < 5%), we imputed missing values for continuous variables using the 'mice' package in R (van Buuren and Groothuis-Oudshoorn 2011). We created 5 imputed datasets and took the average value for further analysis.

Modelling extinction risk

We used random forests (RFs) to predict extinction risk for each species by taxonomic group using the 'randomForests' package in R (Liaw and Wiener 2002). Machine learning predictions from EPBC listing status provides a simple quantification of both the likely probability of threatened status for each species and the level of uncertainty around that prediction. It is also a way to discriminate between species of the same listing class. RFs is suited to modelling extinction risk because it has shown high predictive power compared to other machine learning tools, requires limited assumptions about data types and properties, has relatively high classification and performance, and can cope well with a large number of potentially correlated predictors and non-linear responses (Bland et al. 2015).

We split the data into training (80%) and testing sets (20%). RFs cannot account for phylogenetic relatedness among species, so we included taxonomic order, family and genus as predictors to partially account for shared evolutionary history. Within the training set, we collapsed the EPBC threat status into two classes for the response variable: 'endangered' (Extinct, Critically Endangered, Endangered) and 'threatened' (Vulnerable). We ran our RF models with 500 trees separately for each taxonomic group and predicted the probability of each species belonging to the 'endangered' class.

Surrogacy weightings

We calculated surrogacy weightings for species using the approach presented by Tulloch et al. (2013b). We assumed a species could only be a surrogate for another in belonged to the same taxonomic group. For mammals, birds, frogs, reptiles and invertebrates, we assumed species if it could be a potential surrogate for species *j* if they are found in the same habitat type, have similar behavioural ecology, are subject to the same threats, are of similar body size, and occur in the same place. For fish, we assumed high surrogacy if species share the same habitat type (freshwater, saltwater), are subject to the same threats, and occur in the same place. For plants, surrogacy was high if species shared the same life form, are of similar height and life history (i.e. perennial), are subject to the same threats, and occur in the same location. We collated habitat type and behavioural ecology data from our database of traits described in the extinction risk modelling above. We sourced threat data from a recent project that describes the type and severity of threats for all EPBC listed species in Australia. We only considered threats deemed to be acting in high severity across the full extent of a species range. A more detailed list of the factors influencing surrogacy is presented in Appendix 1.

To calculate surrogacy weightings, we first calculated the pairwise overlap in the geographic range of species. For each taxonomic group, we then constructed binary matrices *H* for each category contributing towards surrogacy (e.g. habitat, behavioural ecology, body size for mammals). Elements in each matrix received a score of 1 (relevant to a species) or 0 (not relevant). Using these matrices, we calculated m-by-m surrogacy matrices where each element q_{ij} describes the ability of species *i* to reflect trends in species *j*, according to:

$$q_{ij}^{h} = 1 - \sum_{l=1}^{w} k_l \left| a_{il} - a_{jl} \right| / w_h \tag{1}$$

where $|a_{il} - a_{jl}| \varepsilon \{0,1\}$, $q_{ij} \varepsilon \{0,1\}$, and h identifying the similarity matrix. We weighted elements of the surrogacy matrices by the proportion of overlapping geographic range, given by the term k_l. The final surrogacy score s_{ij} was calculated by multiplying the similarity matrices *H* for different categories contributing to surrogacy (e.g. habitat type, activity cycle, threats and body mass in the case of mammals), according to:

$$s_{ij} = \prod_{h-1}^{H} q_{ij}^{h} \tag{2}$$

The final surrogacy weighting s_{ij} ranged between zero and one. If the surrogacy value is zero, then a change in the population of species *i* does not imply a likely change in species *j*, whereas a value close to one means that species *i* is a good surrogate of species *j*.

Cost of monitoring

We estimated the cost of monitoring all extant EPBC listed species over a pre-specified time horizon. Following the approach outlined by Stewart et al. (2021), we assumed total monitoring cost consisted of three components: equipment costs, personnel costs and travel costs. Our approach for estimating monitoring cost consisted of 6 steps. We: 1) collated available time-series data for EPBC listed species; 2) conducted a power analysis to estimate the number of sites needed to detect a pre-specified trend in these species during 20 years of monitoring; 3) used results of the power analysis to predict the number of sites needed to detect trends with a high level of confidence in species without time series data; 4) determined the preferred sampling method(s) and survey effort for species to ensure a high chance of detection; 5) calculated the total cost of monitoring species over 20 years; 6) ranked species by their cost-surrogacy ratio while accounting for existing monitoring programs and cost sharing amongst sampling methods (Figure 1). These steps are outlined in more detail below.

Modelling the number of sites needed to detect trends

We obtained time-series data for 38 birds, 38 mammals and 33 plants from the National Environmental Science Programs Threatened Species Index (TSX) website (https://tsx.org.au/). While raw monitoring data were not available for download, species-level data that has been averaged across bioregions are freely available. We assumed aggregated data still provides information on trends and natural variability in population trajectories over space and time. TSX data contained both abundance and occupancy records (averaged across bioregions) depending on the species and primary sampling method(s). We downloaded both data types for our analysis. Further information on the TSX index can be found at Bayraktarov et al. (2021).

We fitted a generalised linear mixed model (GLMMs) to each species in our TSX dataset using the R package 'lme4'. We modelled the trends in abundance over time with site and year random effects to account for natural variability. Using the GLMM fitted to each species, we then calculated the statistical power of detecting a 20% decline in abundance over 20 years using the 'simr' package in R (Green and MacLeod 2016). Power varied across species depending on level of occupancy/abundance, the number of sites and the amount of natural between years and sites. For each species in our TSX dataset, we used the 'simr' package to estimate the number of sites needed to detect a 20% decline in abundance over the next 20 years with 80% power.

Unfortunately, TSX time series data were only available for 109 of the 1893 EPBC listed species. To estimate the number of monitoring sites needed to have high power to detect trends in all EPBC listed species, we fitted a regression model to the power analysis described above. In our model, the response variable n_z was the number of sites needed to detect a 20% decline in species with 80% power and the predictor variables were geographic range size and the expected level of abundance recorded at monitoring sites, given by:

$$n_z = a + b \ln (R_z) + d_{1\text{-}3}L \qquad (3)$$

where a is the intercept, b is the effect of geographic range size R of species z and $d_{1\text{-}3}$ is the effect of different levels of abundance L recorded at monitoring sites. We divided abundance level into 3 classes after exploratory analysis of the TSX data (<10, 10-50 and >50 counts at a site).

For species without TSX time series data, we assigned species a level of expected abundance at monitoring sites based on knowledge of their ecological traits and behaviour. For example, plants and birds at breeding colonies are often recorded with high levels of abundance (>50 individuals) per site, while rare and sparsely distributed species, such as crayfish, are much more likely to be detected at very low levels (<10 individuals per site). Using equation 3, we combined expected levels of abundance with geographic range size to predict the number of monitoring sites needed to detect 20% declines in species abundance with 80% power.

Sampling methods and survey effort

We listed the preferred sampling method(s) for mammals, birds, reptiles, frogs and invertebrates by reviewing published scientific papers, online databases, commonwealth listing and conservation advices, approved and draft species recovery plans, approved threat-abatement plans, species profiles and state government monitoring guidelines. For species with no documented sampling methodology, we assigned sampling method(s) based on similar species from the same taxonomic group. In total, we considered 24 separate sampling across these taxa (Appendix 3). For each sampling method, we reviewed the published and grey literature for best practice guidelines and standards on the minimum number of days/nights that surveys should be repeated to reduce the chance of false negatives. Once again, if information on survey effort was not available for a particular species, we assumed values from similar or related species. Given the large number plants on the EPBC list (1374) and lack of available information on sampling effort, we assumed all species required 2 days of survey effort to reduce the chance of false absences to acceptable levels.

Travel costs

Following the approach by Stewart et al. (2021), we calculated the total travel T_z cost to monitor each species as the sum of: 1) the return travel costs from the closest regional centre to the centre of a species range, and; 2) the travel costs between monitoring sites distributed evenly within the range. To determine return travel costs r, we estimated the travel time in hours from the centre of each species' range to the nearest city with greater than 50,000 inhabitants using a global raster layer of accessibility (Weiss et al. 2018). We assumed all species can be accessed by vehicle, including those found on major islands containing agency headquarters (Tiwi islands, Christmas Island, Lord Howe Island). However, we assumed more remote islands (e.g. Barrow Island) are only accessible by helicopter.

For vehicle travel, we assumed surveyors hire a four-wheel drive ($100 per day) and drive for no longer than 10 hours per day to commence surveys. We assumed a fuel cost of $12 per hour of driving. To calculate travel costs between sites, we assumed sites were evenly distributed across a species range in clusters of four that could be surveyed in the same day/night. We assumed this level of clustering for all sampling methods, although this could be tailored for each different method. We divided the species range size by the total number of clusters to calculate the total area covered by each cluster, then took the square root of this number to approximate the distance between each. We then multiplied this distance by an estimated travel cost per kilometre of $0.26. The total cost of travelling between sites was calculated as the total number of survey days D multiplied by the car hire fee ($100). The total number of survey days was calculated as the number of clusters multiplied by the time spent surveying a cluster (i.e. 4 days). Travel cost was therefore given by:

$$T_z = 2\,(12h_z + 100t_z) + b_{zu}\,(S/4_{iz} - 1) \tag{4}$$

where hz is travel time in hours from the closest city to the geographic range centre of species z and t_z is the number of travel days to commence surveys, b is the cost of travelling between two site clusters, and S is the number of sites.

For species on remote islands that can only be accessed by helicopter, we assumed the travel time to commence surveys was equal to the Euclidean distance to the nearest major city divided by the average flying speed (90 km/hour). We assumed helicopter flying rates were set at $963 per hour for a minimum of 3 hours, with additional landing fees of $919.20 per trip. For species requiring more than one monitoring session, we assumed travel between sessions was also by helicopter at the flying rate reported above (without the landing costs).

Personnel costs and equipment costs

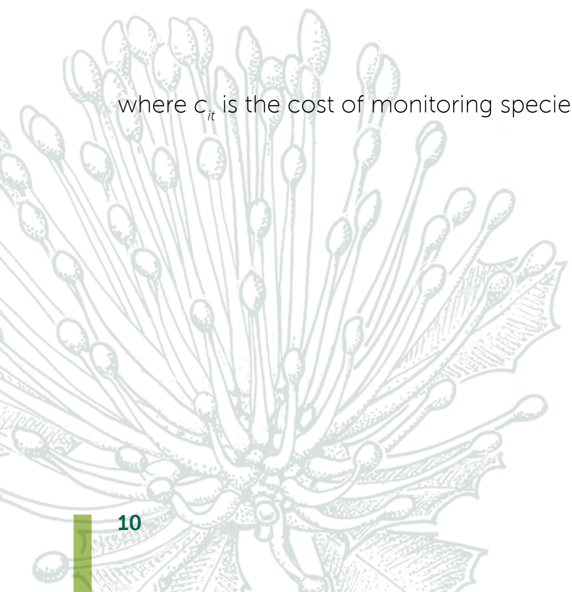
We estimated the personnel costs by multiplying the hourly rate for two experienced surveyors ($100 per hour) by the number of hours per day (10) by the number of survey days D required to adequately visit and survey all sites S. We did not consider the personnel costs required to process monitoring data (such as camera trap photos) or undertake analyses. We estimated the equipment cost for each sampling method and assumed all equipment is purchased at the start of the monitoring time horizon (Appendix 2). We assumed all equipment remains operational for the duration of the monitoring program and that each site cluster requires its own set of equipment.

Total cost over a monitoring horizon

We estimated the annual cost of monitoring for each species by summing travel, personnel and equipment costs. We assumed that all species are monitored each year and calculated the individual cost (c) of monitoring species i over time T, assuming a discount rate γ of 1.4%:

$$C_i = \sum_{t=1}^{T} \gamma^{t-1} c_{it} \tag{5}$$

where c_{it} is the cost of monitoring species i in year t.



Species rankings

We obtained a list of EPBC listed species that are already monitored to some extent from recent studies by Scheele et al. (2019) and Lavery et al. (2021). We ranked species firstly by whether they are already monitored, and secondly, by the cost-benefit ratio CB_i, given by:

$$CB_i = \frac{\sum_i^j E_i S_{ij}}{C_i} \qquad (6)$$

and E_i is the extinction risk of species *i*, S_{ij} is the surrogate weighting of species *i* on species *j* and C_i is the total cost of monitoring species *i*. In this equation, the highest ranked species are those that have a high extinction risk, are good surrogates (surrogacy weightings summed across species), and are relatively cheap to monitor.

We adjusted our cost-benefit ranking to account for cost-efficiencies in monitoring. To do this, we developed a greedy algorithm in R that iteratively stepped through each species starting with those that are already monitored. For species *i*, we adjusted the cost-benefit ratio of species *j* by the proportional overlap in their ranges if both species: 1) belonged to the same taxonomic group, and; 2) are detected with the same sampling method(s). For example, if the range of species i overlaps with 50% of species *j*, and both come from the same taxonomic group and are detected with the same detection methods, the monitoring costs of species B were halved. The algorithm re-calculated the cost-benefit ratio for species *j*, then sequentially searched for the next most cost-effective species, before repeating the adjustment in cost-sharing. The final outcome was a list of species ranked by their cost-benefit ratio that had been adjusted opportunities for cost-sharing.

Monitoring helps us to understand the status, distribution and trends of threatened species. Macquarie University PhD student Tom Pyne undertaking a flora survey in Ku-Ring-Gai National Park NSW. Image: Rachel Gallagher

Results

Modelling extinction risk

Species with the highest predicted extinction risk/vulnerability based on intrinsic traits were dominated by plants and invertebrates. Of the 30 highest ranked species, 16 were plants, 12 were invertebrates and 2 were frogs (Table 2). Eighteen of these are currently ranked as Critically Endangered and 12 as Endangered. Only 5 of the top ranked species with the highest predicted extinction risk are monitored already. The highest ranked species were dominated by orchids and invertebrates with small distributions.

Table 2. *Top 30 EPBC listed species with the highest predicted extinction risk based on intrinsic ecological traits*

Group	Species	Status	Extinction risk	Already monitored
Plant	*Caladenia campbellii*	CR	1	No
Plant	*Caladenia sp. Kilsyth South (G.S.Lorimer 1253)*	CR	1	No
Plant	*Caladenia tonellii*	CR	1	No
Plant	*Calochilus richiae*	EN	1	No
Plant	*Prasophyllum favonium*	CR	1	No
Invertebrate	*Cherax tenuimanus*	CR	1	No
Invertebrate	*Dryococelus australis*	CR	1	No
Invertebrate	*Phyllodes imperialis smithersi*	EN	1	No
Invertebrate	*Placostylus bivaricosus*	EN	1	No
Invertebrate	Pseudocharopa ledgbirdi	CR	1	No
Invertebrate	Pseudocharopa whiteleggei	CR	1	No
Invertebrate	Pseudococcus markharveyi	CR	1	Yes
Invertebrate	Semotrachia euzyga	EN	1	No
Plant	Caladenia amoena	EN	0.998	No
Plant	Caladenia pumila	CR	0.998	No
Plant	Caladenia saggicola	CR	0.998	No
Invertebrate	Engaewa pseudoreducta	CR	0.998	No
Invertebrate	Micropathus kiernani	CR	0.998	No
Frog	Cophixalus concinnus	CR	0.996	No
Plant	Caladenia atroclavia	EN	0.996	No
Plant	Caladenia rosella	EN	0.996	No
Plant	Calochilus psednus	EN	0.996	No
Plant	Corunastylis brachystachya	EN	0.996	No
Plant	Corunastylis ectopa	CR	0.996	Yes
Plant	Corunastylis insignis	CR	0.996	Yes
Invertebrate	Quintalia stoddartii	CR	0.996	Yes
Invertebrate	Sinumelon bednalli	EN	0.996	No
Frog	Taudactylus pleione	CR	0.994	Yes
Plant	Caladenia conferta	EN	0.994	No
Plant	Caladenia dienema	EN	0.994	No

Surrogacy values

The ranking of species was highly sensitive to surrogacy potential. The top 30 ranked species were entirely dominated by plants. This is due to the relatively sheer number of plants, and our assumption that surrogacy cannot occur across taxonomic groups. Of the top 30 ranked species, 5 are listed as Vulnerable, 12 as Endangered and 12 and Critically Endangered (Table 3). Vulnerable species made up a high proportion of the top ranked species compared to when species were ranked by predicted extinction risk alone because species were more likely to be good surrogates if they were subject to common threats and were widespread. Fourteen of the top 30 ranked species are already monitored.

Table 3: *Top 30 ranked EPBC listed species based on the surrogacy scores*

Group	Species	Status	Surrogacy score	Monitored already
Plant	*Phreatia paleata*	EN	9.856673	Yes
Plant	*Tmesipteris norfolkensis*	VU	9.549758	No
Plant	*Phreatia limenophylax*	CR	9.479773	Yes
Plant	*Blechnum norfolkianum*	EN	9.357071	Yes
Plant	*Lastreopsis calantha*	EN	9.321803	Yes
Plant	*Elatostema montanum*	CR	9.103418	Yes
Plant	*Ptilotus pyramidatus*	CR	8.88533	No
Plant	*Prasophyllum olidum*	CR	8.111028	No
Plant	*Prasophyllum taphanyx*	CR	8.111028	No
Plant	*Grevillea thelemanniana*	CR	7.907108	No
Plant	*Leucopogon gnaphalioides*	EN	7.735633	No
Plant	*Coprosma pilosa*	EN	7.256364	Yes
Plant	*Darwinia collina*	EN	7.239402	No
Plant	*Ileostylus micranthus*	VU	7.047429	No
Plant	*Clematis dubia*	CR	6.986112	Yes
Plant	*Euphorbia norfolkiana*	CR	6.938037	Yes
Plant	*Pteris zahlbruckneriana*	EN	6.911264	Yes
Plant	*Senecio evansianus*	EN	6.798841	Yes
Plant	*Melicope littoralis*	VU	6.785396	No
Plant	*Melicytus latifolius*	CR	6.785396	Yes
Plant	*Zehneria baueriana*	EN	6.785396	Yes
Plant	*Darwinia squarrosa*	VU	6.694434	No
Plant	*Oberonia attenuata*	CR	6.64	No
Plant	*Latrobea colophona*	CR	6.432569	No
Plant	*Calytrix breviseta subsp. breviseta*	EN	6.404267	No
Plant	*Daviesia glossosema*	CR	6.346473	No
Plant	*Hypolepis dicksonioides*	VU	6.273296	Yes
Plant	*Pteris kingiana*	EN	6.273296	Yes
Plant	*Eremophila ternifolia*	EN	6.248681	No
Plant	*Thelymitra cyanapicata*	CR	6.115543	No

Monitoring costs

When extinction risk, surrogacy and cost were considered, the top 30 ranked species consisted of 20 birds, 8 plants and 2 mammals (Table 4). Of these, 13 are already monitored to some extent. Species that ranked highly were generally relatively cheap to monitor because they: 1) are found close to major centres; 2) do not require expensive equipment, and 3) require relatively few sites to detect a population change due of high levels of abundance at sites. Our results suggest that the annual cost of monitoring all 1893 EPBC listed species so that 20% declines can be detected with 80% confidence is AUD $307 million. If species that are monitored to some degree are removed, then the total annual cost is AUD $148 million.

Table 4: *Top 30 ranked EPBC listed species based on extinction risk, surrogacy and cost.*

Group	Species	Status	Surrogacy score	Cost per year (AUS dollars)	Already monitored
Bird	*Calidris tenuirostris*	CR	3.699198	5885.717	Yes
Plant	*Persoonia micranthera*	EN	4.998752	8315.185	No
Plant	*Banksia anatona*	CR	3.673416	8321.255	No
Bird	*Charadrius mongolus*	EN	3.612161	8375.016	No
Bird	*Numenius madagascariensis*	CR	2.832523	6648.258	Yes
Bird	*Charadrius leschenaultii*	VU	3.198867	9199.998	Yes
Plant	*Caladenia gladiolata*	EN	3.600514	10648.82	No
Bird	*Calidris ferruginea*	CR	2.733895	8640.265	Yes
Plant	*Caladenia woolcockiorum*	VU	4.32872	15528.89	No
Plant	*Caladenia behrii*	EN	5.199436	20311.01	No
Bird	*Calidris canutus*	EN	3.668867	20369.26	No
Plant	*Isoglossa eranthemoides*	EN	1.374093	8250.223	Yes
Mammal	*Parantechinus apicalis*	EN	0.793488	4851.015	Yes
Plant	*Senecio macrocarpus*	VU	2.479852	17982.73	Yes
Bird	*Calyptorhynchus lathami halmaturinus*	EN	1.411378	11844.48	Yes
Bird	*Neophema chrysogaster*	CR	1.89263	16218.16	Yes
Plant	*Isopogon uncinatus*	EN	1.982787	17993.81	No
Plant	*Grevillea maxwellii*	EN	1.718489	17991.03	No
Plant	*Prasophyllum olidum*	CR	8.111028	86342.97	No
Plant	*Prasophyllum taphanyx*	CR	8.111028	86342.97	No
Plant	*Phreatia paleata*	EN	9.856673	106826.9	Yes
Plant	*Asplenium wildii*	VU	5.435977	59313.59	No
Plant	*Tmesipteris norfolkensis*	VU	9.549758	104338.6	No
Plant	*Ranunculus prasinus*	EN	5.856508	64198.46	No
Plant	*Phreatia limenophylax*	CR	9.479773	104338.6	Yes
Plant	*Blechnum norfolkianum*	EN	9.357071	104338.8	Yes
Plant	*Vrydagzynea grayi*	EN	5.724846	64202.27	No
Plant	*Chingia australis*	EN	4.589625	52048.28	No
Mammal	*Gymnobelideus leadbeateri*	CR	1.627551	18464.14	Yes
Plant	*Caladenia anthracina*	CR	4.999221	56856.56	No

Ranking of species with cost sharing

We estimated the annual cost of monitoring all EPBC listed species with cost sharing is $AUD 179 million. If we take out species already monitored, this total reduces to AUD $74 million (Table 5).

Table 5: *Top 30 ranked EPBC listed species that are yet to be monitored with cost sharing*

Group	Species	Status	Extinction risk	Surrogacy score
Mammal	*Rhinonicteris aurantia (Pilbara form)*	VU	0.206	0.206
Bird	*Diomedea antipodensis*	VU	0.148	1.069662
Bird	*Melanodryas cucullata melvillensis*	CR	0.88	1.574978
Plant	*Allocasuarina robusta*	EN	0.752	4.921212
Mammal	*Petaurus australis Wet Tropics subspecies*	VU	0.346	1.727191
Bird	*Thalassarche cauta cauta*	VU	0.102	1.398709
Bird	*Thinornis rubricollis rubricollis*	VU	0.2	2.804579
Plant	*Leionema ralstonii*	VU	0.222	1.610538
Plant	*Eucalyptus paludicola*	EN	0.81	0.81
Plant	*Prasophyllum innubum*	CR	0.988	3.083727
Bird	*Thalassarche bulleri*	VU	0.146	0.873136
Plant	*Grevillea molyneuxii*	EN	0.672	2.069346
Plant	*Bertya ernestiana*	VU	0.272	0.900458
Plant	*Almaleea cambagei*	VU	0.452	1.683017
Plant	*Phebalium whitei*	VU	0.31	2.252477
Plant	*Kardomia granitica*	VU	0.146	1.286628
Plant	*Leucopogon confertus*	EN	0.768	1.637312
Plant	*Caladenia robinsonii*	EN	0.894	2.801345
Plant	*Prasophyllum colemaniae*	VU	0.818	2.782238
Plant	*Boronia granitica*	EN	0.466	1.171342
Plant	*Acacia macnuttiana*	VU	0.346	1.326242
Plant	*Homoranthus lunatus*	VU	0.244	1.103277
Plant	*Eucalyptus caleyi subsp. ovendenii*	VU	0.14	0.40587
Plant	*Caladenia pumila*	CR	0.998	3.259437
Plant	*Corybas montanus*	VU	0.506	1.862611
Plant	*Westringia cremnophila*	VU	0.248	1.066952
Plant	*Homoranthus montanus*	VU	0.094	0.26741
Plant	*Epacris limbata*	CR	0.89	3.399021
Plant	*Bothriochloa bunyensis*	VU	0.294	1.700444
Plant	*Caladenia atroclavia*	EN	0.996	1.634897

Discussion

Given Australia is in the midst of an extinction crisis, there is a need for repeatable approaches for quantifying the cost of monitoring threatened species and for prioritising the allocation of resources amongst species (Nicholson and Possingham 2006, Rodrigues and Brooks 2007). Cost-efficient monitoring will improve understanding of status and trends while informing management decisions. Previous prioritisation approaches generally use scoring or ranking methods (Rice and Rochet 2005, Tulloch et al. 2011), which in their simplest form does not account for uncertainty, surrogacy, or cost sharing. In this report, we: 1) compiled a national database on traits, survey methods and costs for EPBC listed species; 2) quantified extinction risk based on intrinsic ecological traits; 3) estimated the ability of species to act as surrogates for others given shared threats, ecology, habitat requirements and overlapping geographic range, and; 4) estimated the cost of detecting trends in species with a high level of confidence given preferred sampling methods and while accounting for cost sharing. Our approach can be applied to a large number of species and is data driven, not relying on expert opinion. We showed that by combining both transparent expenditure and extinction risk, decision makers can make rational, efficient, and informed prioritisation choices that maximize conservation outcomes.

Cost of monitoring all species

We developed a novel framework for estimating the cost of monitoring species across the full extent of their range using the best available information on preferred sampling methods and detectability. Our approach utilised real time series data to quantify how many monitoring sites are needed to detect small-to-moderate (20%) decline in populations with 80% power, which was a key driver of overall monitoring costs. We are not aware of any attempts to model power in such a way across a large set of species at a continental scale. Our results suggest that it will cost AUD $179 – 307 million per year to monitor all 1893 EPBC listed species with high levels of power to detect small-to-moderate trends over the next 20 years. The lower bound of this estimate accounts for a scenario of cost sharing, while the upper bound assumes only a single target species is recorded during surveys. If we remove species that are already monitored to some extent, then annual costs reduce to between AUD $74 – 179 million, depending on the degree of cost sharing. However, we note that of the species that are already monitored, few are done so with high levels of power. This means that further investment in these species is likely needed to ensure further population declines have a high chance of being detected. Our estimates of total monitoring costs are in general agreement with previous studies; for example, Wintle et al. (2019) concluded that $842 million – 2.5 billion/year is needed to recover all Australian species threatened with extinction.

Most consistently ranked group

Our ranking of species was highly sensitive to whether surrogacy, cost and cost sharing was included in the ranking method. Regardless of the method, plants were consistently ranked in the top set of indicator species. Plants consistently ranked highly for a number of reasons. Firstly, they dominate the EPBC list by sheer numbers; 73% of threatened species are plants (as of 2019). Secondly, plants had relatively high surrogacy scores, partly due to a relatively small number of potential threats compared to other taxonomic groups, but also again because of the high proportion of plants in our candidate species set. Thirdly, our analysis of real TSX time series data revealed high levels of abundance at monitoring sites (>50 counts), which meant that relatively few sites were needed in our power analysis to detect further declines with a high level of power. This significantly reduced annual monitoring costs compared to other taxonomic groups that are likely detected in very small numbers during monitoring. Finally, plants made up the majority of top ranked species in our cost sharing scenario because very few plants are already monitored to some extent. A recent paper by Tyrone et al (2021) found that only very few of EPBC listed plants are monitored; however, this figure is an under-estimate because species in Tasmania and Western Australia were not assessed. However, including these additional species would likely not affect the number of plants in a top set of rankings.

Top ranked species within a group

The highest priority species within each taxonomic group were a mix of wide-ranging umbrella species whose cost-effective monitoring likely provided an indicator of the trends in many other species. For example, shorebirds were prioritised highly because they have wide-ranging distributions and thus were assumed to act as indicators for many other species. The TSX data also revealed that these species are detected in high numbers at monitoring sites, which meant that they were relatively cheap to monitor because few sites were needed to detect declines with a high level of confidence. In contrast, narrow ranging species were sometime ranked highly if they were cheap to monitor and overlapped with other species with narrow distributions. For example, birds on Christmas Island were ranked highly because they had relatively high surrogacy and extinction risk scores, are subject to the same threats, have similar ecology and behaviour and have overlapping distributions.

Trait based extinction risk vs expert elicitation

We modelled extinction risk using EPBC listing status and intrinsic traits to provide a simple quantification of the likely probability of being threatened or vulnerable and so that we could discriminate between species of the same listing class. We acknowledge that there might be some circularity in this approach if species are mostly listed based on any one of our predictor variables, such as range size. Our estimates of extinction risk could have been extended to include extrinsic traits, such as habitat degradation, habitat suitability of predators, human footprint index, human population density, global forest loss, human influence index (Bland et al. 2017). For example, Murray et al. (2011) modelled whether species were decreasing or increasing as a function of intrinsic traits that make some species susceptible to decline or extinction, along with spatial models of the multiple key threats (disease, invasive species, habitat destruction). This approach is an important avenue of future research but would require accurate spatial layers of key threatening processes influencing extinction, such as the distribution of predators like foxes and cats.

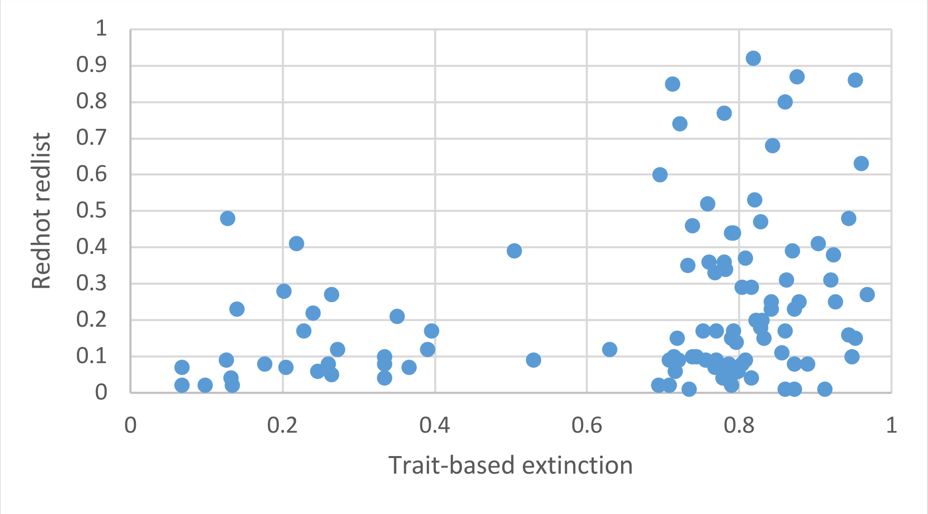


Figure 2: *Correlation between trait-based extinction risk derived in this study and expert elicited probabilities of extinction.*

Rather than predict extinction risk based on intrinsic ecological traits, an alternative approach is to rely on expert derived probabilities of extinction (i.e. how likely a species will go extinct in near future). Extinction probabilities were recently elicited from experts for a subset of EPBC listed species following a formal expert elicitation process (Lintermans et al. 2020, Geyle et al. 2021a, Geyle et al. 2021b). We initially considered using these values in our benefit function as they probably better reflect the near-term fate of threatened species in Australia; however, they were only available for 20 species in each taxonomic group and for none of the plants, which make up 73% of listed species. We therefore adopted our approach which allowed for all EPBC listed species to be assessed. We did, however, explore the correlation between our trait-based extinction estimates and expert derived probabilities of extinction. Plotting them against each other revealed moderate disagreement. In particular, many species predicted to have a high risk of extinction in our study were considered low risk by experts. If the expert elicitation is extended to all species, the values could be substituted into our prioritisation framework for comparison.

Additional weightings to extinction risk

Our framework combined information on extinction risk (determined by status listing and intrinsic traits), surrogacy (determined by threats, habitat requirements, behavioural ecology range overlap), and cost (driven by sampling method, equipment costs and the number of sites). It might be important to include a way of increasing the value for a species if a major threat has recently been detected (e.g. myrtle rust) and the rate of decline (and hence need for timely monitoring) is expected to increase as a result. Decision-makers may wish to weight species by other factors not included here, such as taxonomic distinctiveness, cultural significance, economic value, ecosystem services, value to the public (Joseph et al. 2009; Bennett et al. 2014). For example, Roll et al (2016) examined characteristics that make certain reptile species of greater cultural significance. Future research could add extra weightings of extinction risk to account for such factors. Another factor we did not consider is management effectiveness. We assumed that monitoring information on the status and trends trigger effective management intervention. It may be optimal to prioritise monitoring towards species whose response to management is most uncertain, so that further investment in that species can be resolved. However, this requires information on management effectiveness for all species, which is difficult to obtain.

Further research

Our framework could be further extended in a number of ways. For example, we estimated the cost of monitoring with the pre-specified goal of detecting 20% declines in populations with 80% power. We could repeat our analysis with different levels of power and target levels of decline to explore how this influences total monitoring cost. Relaxing the degree of change one wishes to detect as well as the level of power will reduce overall monitoring costs as fewer sites are needed. Our framework could also be expanded to include new and emerging technologies, which have potential to substantially reduce costs and increase opportunities for multi-species detections and single monitoring sites. In particular, eDNA, acoustic recorders and motion triggered cameras should provide access to large amounts of data across spatial and temporal scales, and such methods should become cheaper in future as the technology develops. Furthermore, increasing involvement of citizen scientists and volunteers is an opportunity to decrease monitoring costs for threatened species, and our framework could be expanded to include this type of data collection. However, while citizen scientists can increase the spatial and temporal resolution of sampling, they introduce sampling bias and thus may not result in monitoring having desired levels of power to detect population trends. Finally, we assumed all species were monitored each year and did not specify species-specific survey frequencies. An important area of future research is assigning each species a survey frequency so that total monitoring costs over a 20 year horizon considers such information.

Conclusions

Until all species can be effectively monitored, prioritization methods that maximize efficiency are necessary because there is generally limited availability or allocation of resources toward conservation. Our approach provides an estimate of how much it might cost to monitor all EPBC listed species in Australia, and provides a way to rank species when strict budgets are only available.

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Threatened orchids (Caladenia caudata *pictured) were some of the highest-ranked species and overall, receive little monitoring. Image: DPIPWE*

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Appendix 1: Factors contributing to surrogacy by taxonomic group

Group	Habitat	Ecology	Body size	Threats
Mammals	Aquatic, saxicoline, arboreal, ground-dwelling	Octurnal, diurnal, cathemeral	<10g, 10-50g, 50-5000g, >5000g	invasive vertebrate (cats), invasive vertebrate (foxes), recreational activities, inappropriate fire regimes, habitat loss, fragmentation, disease, invasive vertebrate (cane toad), climate change & severe weather, invasive plant (weeds), dingo/ dog/ wild dog, livestock grazing
Birds	Forest, savanna, shrubland, grassland, wetlands, rocky areas, caves, desert, marine		<10g, 10-50g, 50-5000g, >5000g	climate change (sea-level rise), inappropriate fire regimes, invasive vertebrate (cats), livestock grazing, invasive vertebrate (goats), invasive vertebrate (foxes), problematic native bird, climate change & severe weather, forestry, invasive invertebrate (bee), fisheries, invasive vertebrate (pigs), invasive vertebrate (cattle), invasive vertebrate (sugar glider), disease (psittacine beak and feather disease), loss of genetic diversity, invasive plant (weeds), invasive invertebrate (botfly), energy production & mining, habitat degradation, invasive vertebrate (rodents), herbicides and pesticides, agriculture (cropping)
Reptiles	Terrestrial, arboreal, fossorial, saxicolous, aquatic	Octurnal, diurnal, cathemeral		agriculture (cropping), invasive vertebrate (wolf snakes), livestock grazing, inappropriate fire regimes, invasive species (unk0wn)
Frogs	Fossorial, terrestrial, aquatic, arboreal	Octurnal, diurnal, cathemeral		climate change & severe weather, disease, invasive vertebrate (fish), habitat loss, inappropriate fire regimes
Invertebrates	deep burrow, shallow burrow <10cm, under rock, in soil, under logs, under bark, ground living, leaf litter on ground, elevated leaf litter, vegetation, standing wood, large shrubs, estuary, 0 shelter,	disp_<10m, disp_100-1000m, disp_1km-10km, disp_10km+, disp active_flight, disp_ obligate disp, disp_ low to 0 dispersal		invasive vertebrate (rodents), invasive plant (lantana), livestock grazing, inappropriate fire regimes, invasive vertebrate (pigs), invasive invertebrate (yellow crazy ant), habitat loss, altered hydrology, invasive vertebrate (cane toad), invasive invertebrate (african big-headed ants), disease (phytophthora), climate change & severe weather

Group	Habitat	Ecology	Body size	Threats
Plants	Tree, shrub, prostrate, shrub tree, herb, herb_large, tussock, grami0id_tussock_tall, climber_vine, prostrate_shrub, prostrate_herb, fern, grami0id, grami0id_tussock, climber_vine_herbaceous, short_basal, climber_liana, climber, fern_tree, cycad, grami0id, _0t_tussock_tall, treelet, hemi-parasite parasite, grami0id_0t_tussock, macrophyte, subterranean trunk, sub_shrub, climber_scrambler, liverwort, semi_basal, algae		<1m, 1-5m, 5-10m, >10m	invasive species (unk0wn), habitat degradation, habitat loss, inappropriate fire regimes, energy production & mining, altered hydrology, agriculture (plantations), drought, livestock grazing, disease, hunting and collecting terrestrial animals,

Appendix 2: Survey costs

Financial costs of each method utilised within the analysis. Units costs are set to $No if surveys are conducted by a fully equip organisation. Survey duration is based on estimates from published guidelines and grey literature (see Appendix H). All values are in Australian dollars.

Detection method	Survey duration (minutes)	Hourly rate (AU)	Unit	Unit cost
Acoustic survey	160	60	1	300
Active search	360	60	0	0
Arboreal camera	2.25	60	9	900
Automated acoustic monitor	45	60	5	1200
Cage traps	150	60	10	40
Cover trap	165	60	20	4
Detection dog	480	125	0	0
Electrofishing	240	60	1	1500
Elliott/Sherman trap	135	60	10	30
Environmental DNA	120	60	2	80
Fyke net survey	120	60	3	300
Ground count survey	60	60	0	0
Hair tube survey	45	60	10	17
Handheld thermal camera survey	240	60	1	1100
Harp trap	60	60	2	2000
Mist net trap	60	60	2	150
Motion trigger camera trap	75	60	9	900
Nest box count survey	120	60	10	60
Pitfall trap	195	60	10	15
Point count survey	240	60	0	0
Spotlight survey	240	60	1	600
Tapdole dipnet survey	120	60	1	15
Taxonomic ID	60	60	0	0
Track and sign survey	240	60	0	0

Appendix 2: Predicted extinction risk

Mammals

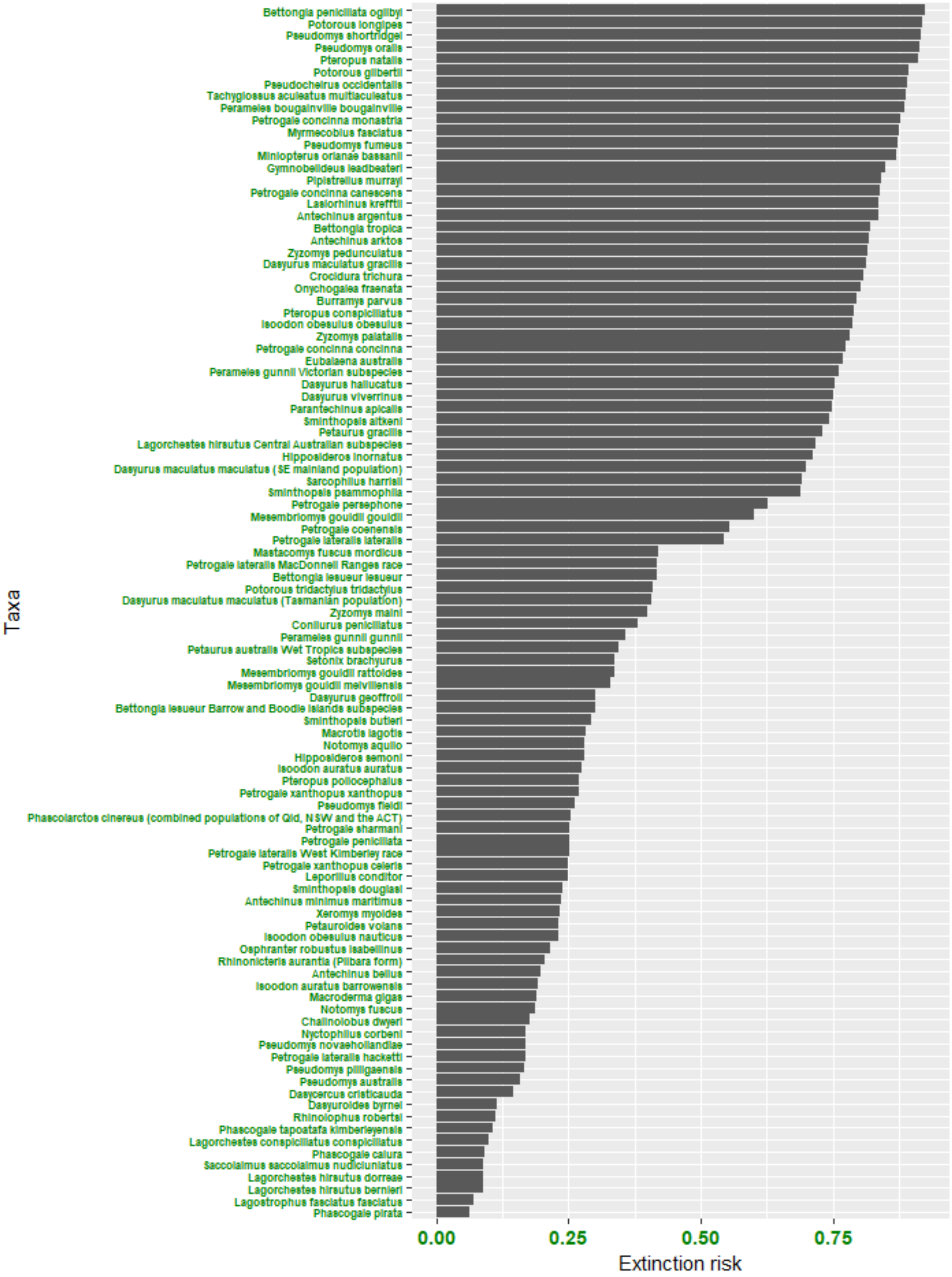

Figure S1: *Mammal extinction risk*

Birds

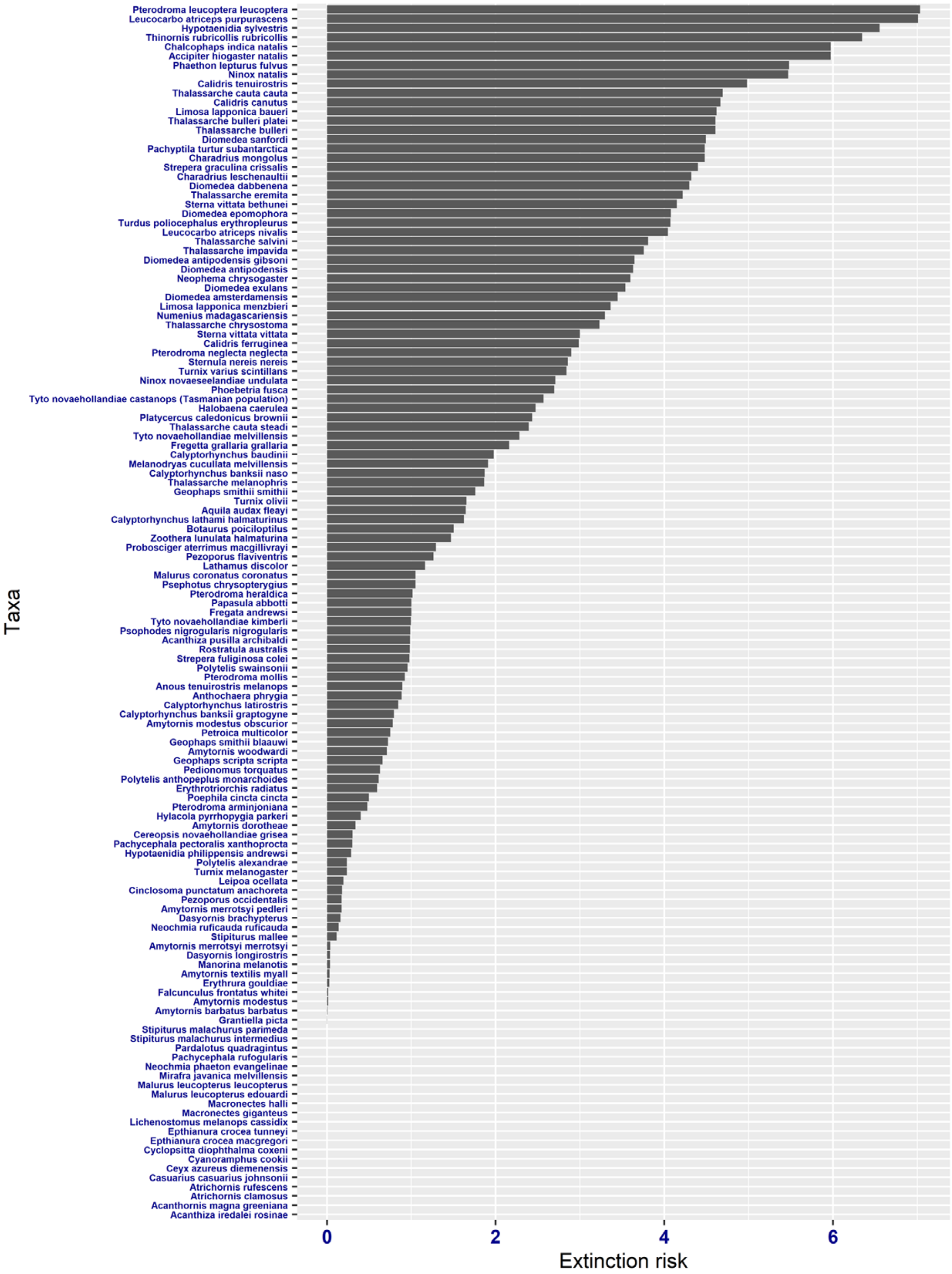

Figure S2: *Bird extinction risk*

Frogs

Figure S3: *Frog extinction risk*

Reptiles

Figure S4: *Reptile extinction risk*

Plants

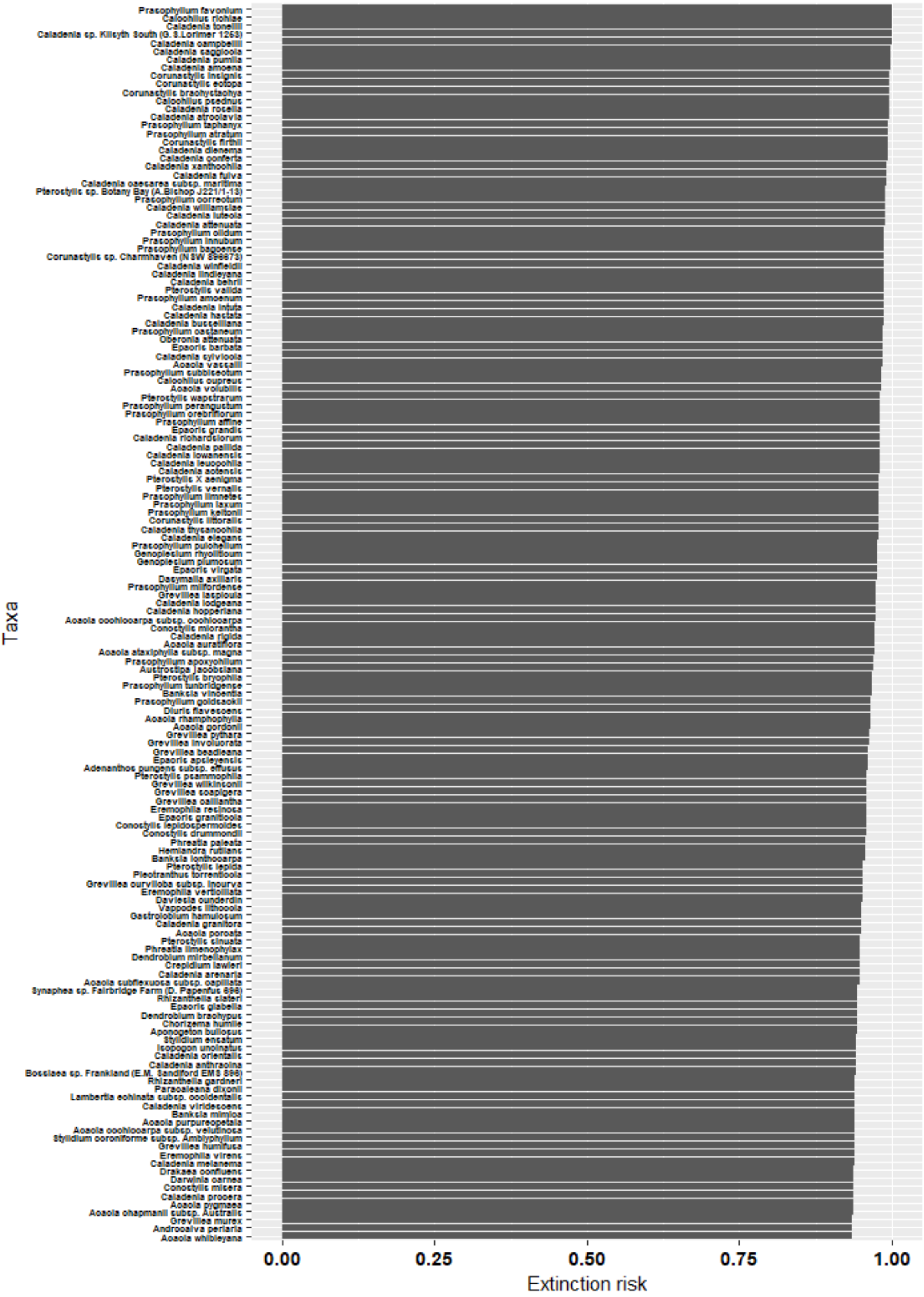

Figure S5: *Plant extinction risk*

Fish

Figure S6: Fish extinction risk

Invertebrates

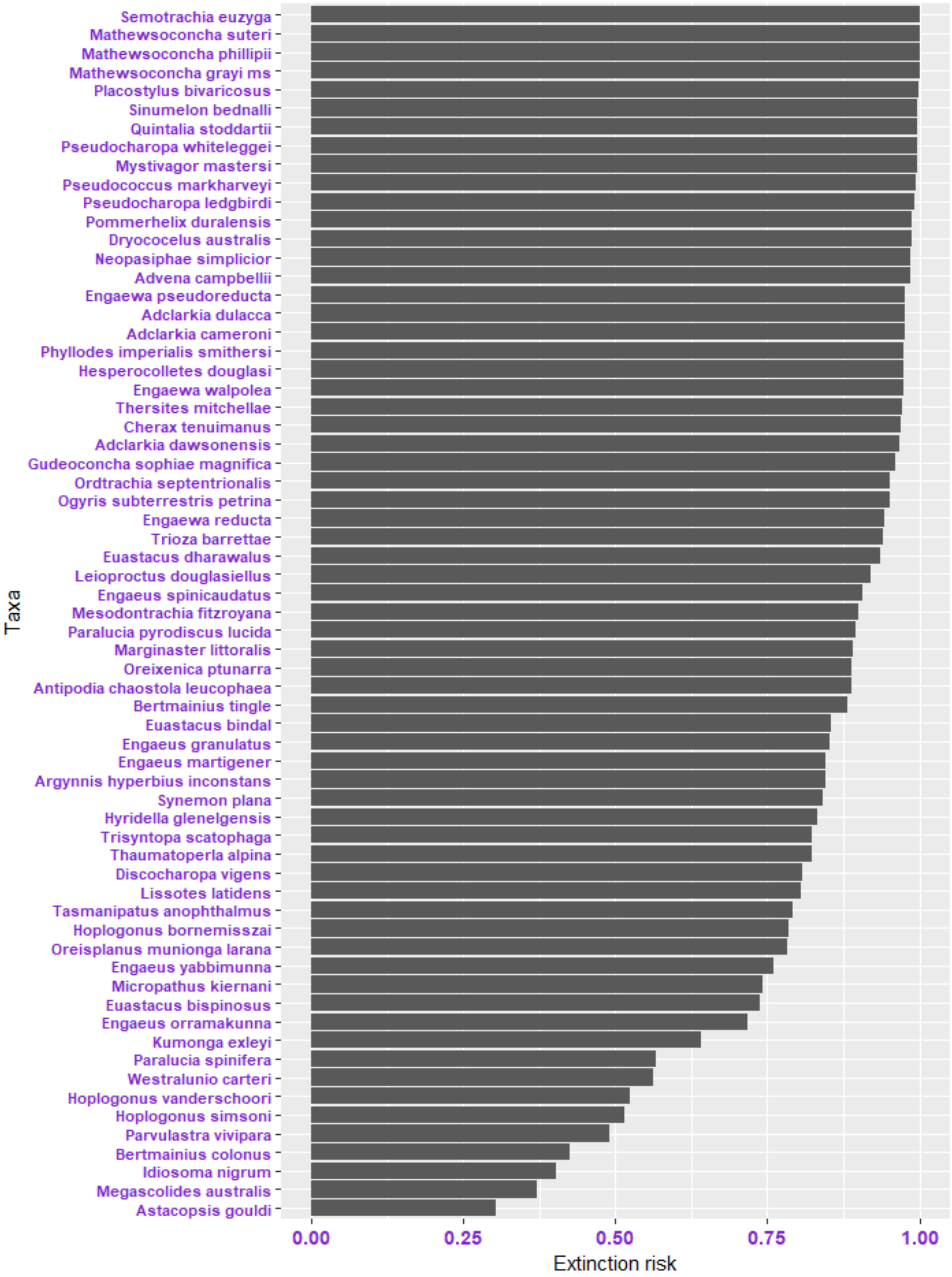

Figure S7: *Invertebrate extinction risk*

Appendix 2: Surrogacy scores

Mammals

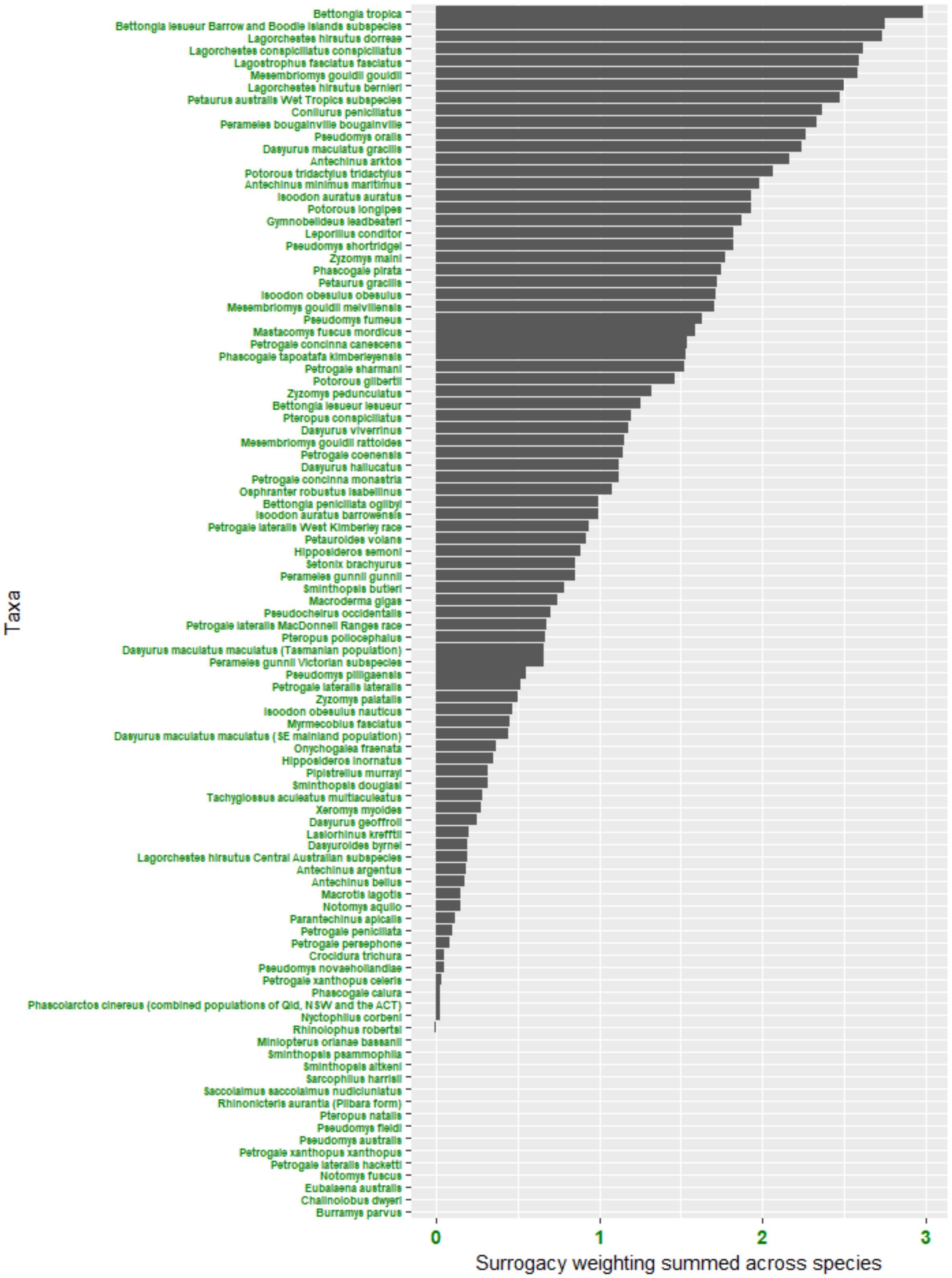

Figure S8: Mammal surrogacy scores

Birds

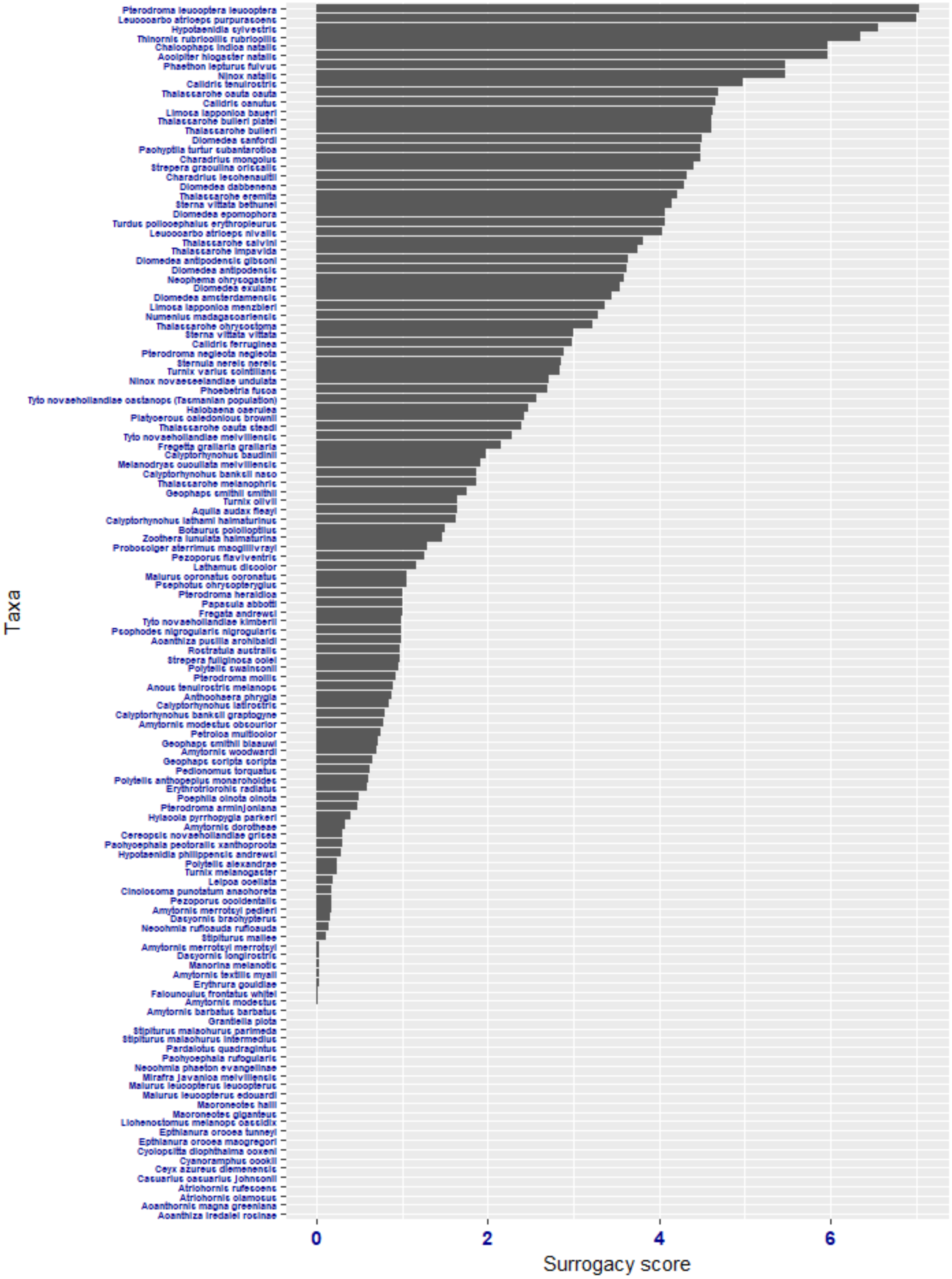

Figure S9: *Bird surrogacy scores*

Frogs

Figure S10: Frog surrogacy scores

Reptiles

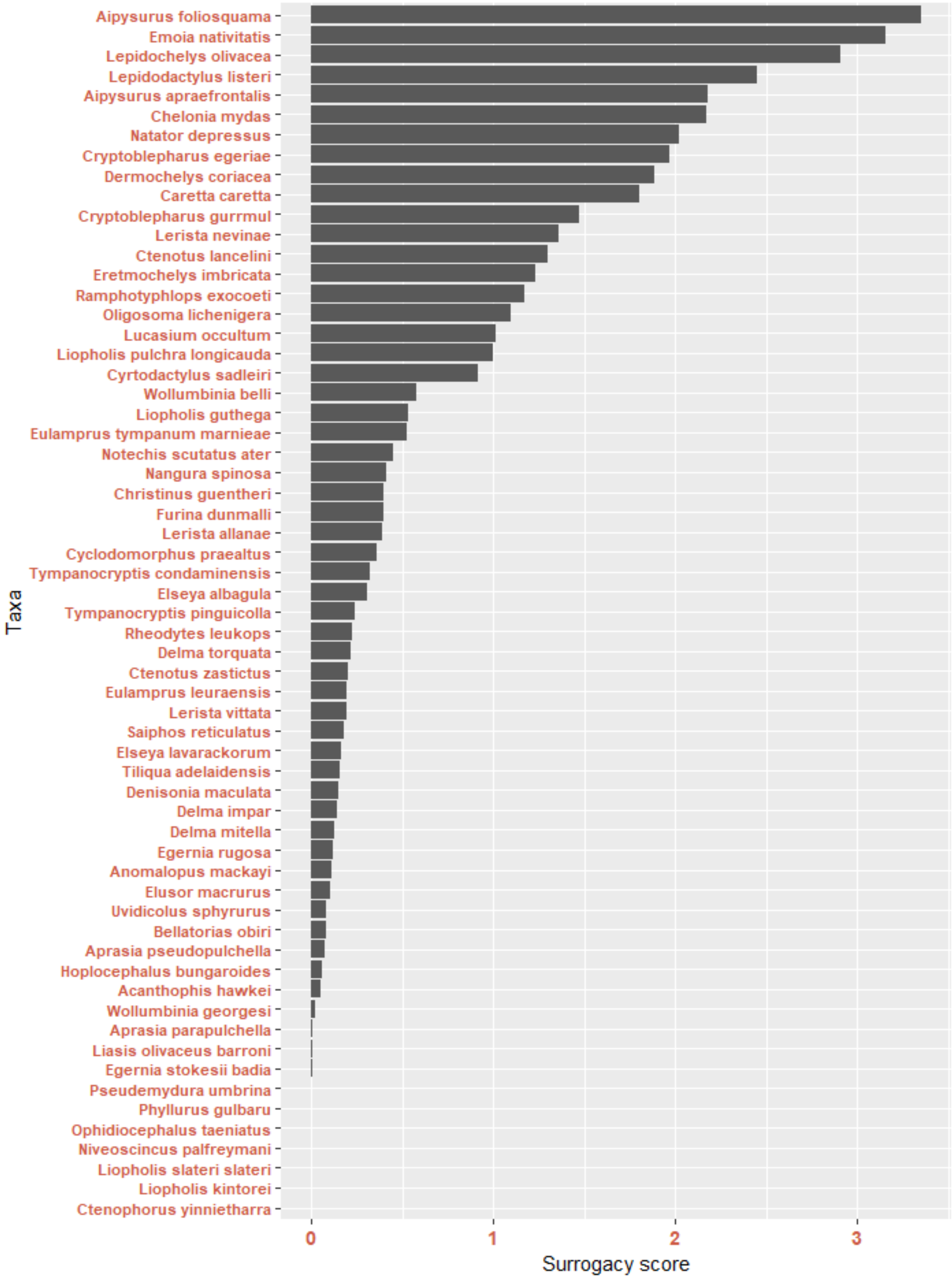

Figure S11: Reptile surrogacy scores

Plants

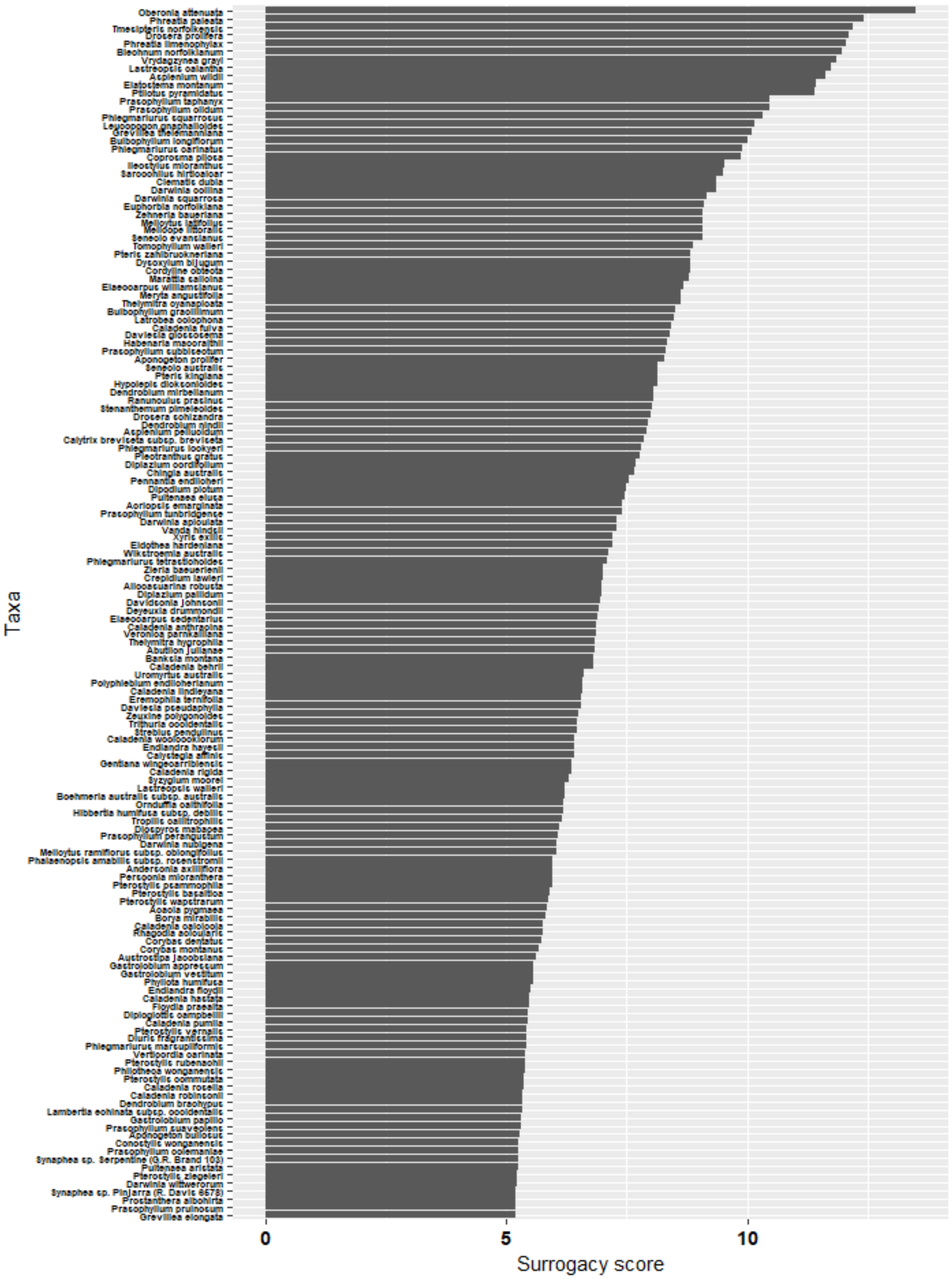

Figure S12: *Reptile surrogacy scores*

Fish

Figure S13: *Fish surrogacy scores*

Invertebrates

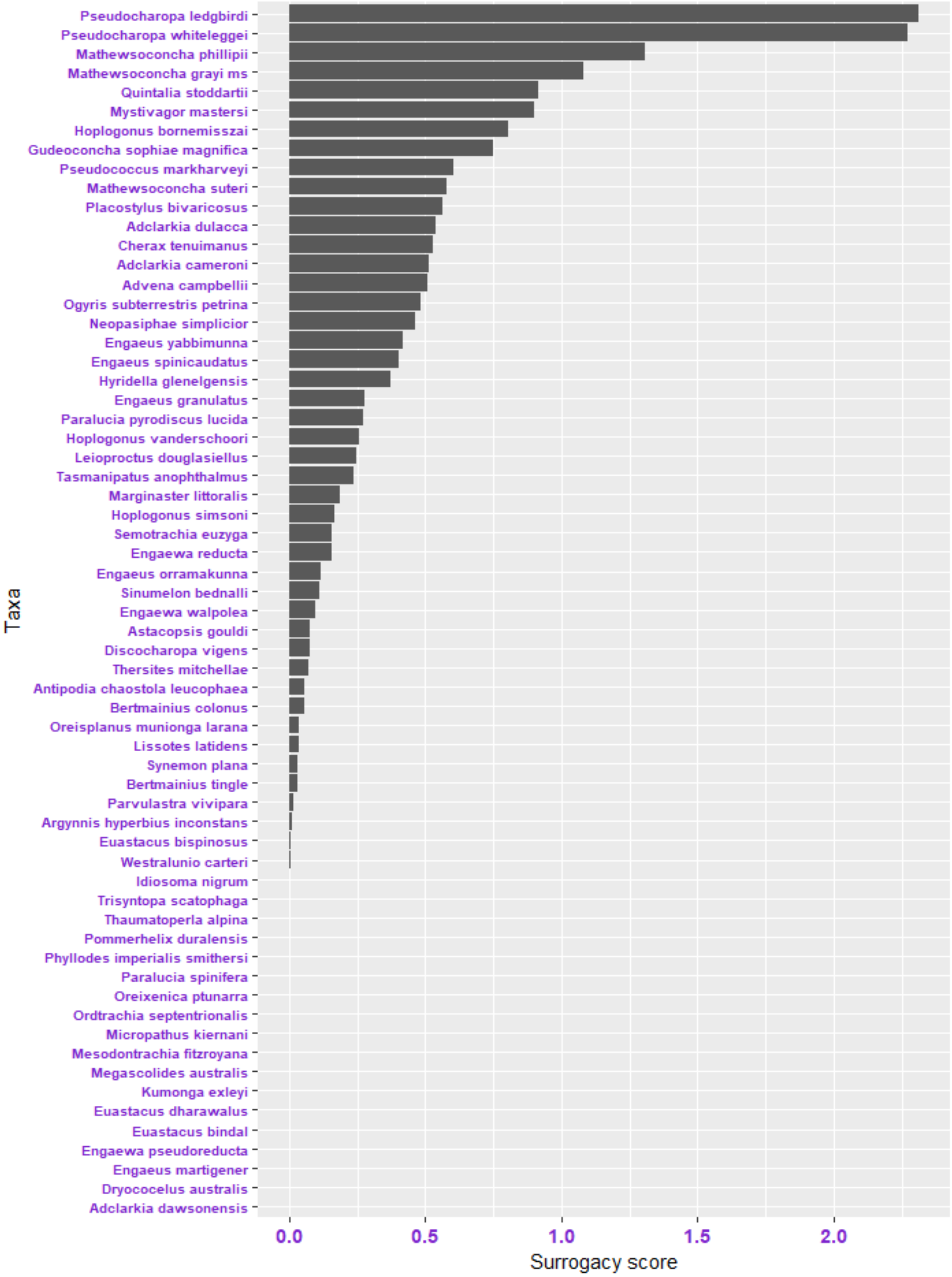

Figure S14: *Invertebrate surrogacy scores*

Further information:

http://www.nespthreatenedspecies.edu.au

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