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RESEARCH ARTICLE

Inferring the extinction risk of Data Deficient and Not Evaluated Australian squamates

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Abstract

The world is facing a biodiversity crisis, and species are in danger of slipping towards extinction before having their conservation status formally determined. Australian squamates (snakes and lizards) form a highly diverse (over 1000 species) fauna, with 12% being either Data Deficient or Not Evaluated. We examined attributes of Australian squamates categorized as Data Deficient or Not Evaluated and compared key traits that are linked with threatened categories via univariate and multivariate models. We further used the machine learning model of Caetano et al. (2022, PloS Biology, 20, e3001544) to predict the putative extinction risk categories for Data Deficient and Not Evaluated Australian squamate species based on an analysis of reptiles globally. We found that Data Deficient Australian squamates are often lacking information on their drivers of threat and distribution, but not intrinsic traits or uncertain taxonomy. Data Deficient, Not Evaluated and threatened species often possess similar traits, including having small range sizes, being insular endemics and recently described, indicating that they may require some similar conservation management. Meanwhile, Not Evaluated species exhibit certain unique traits relative to evaluated species. We predicted 21% of Data Deficient and Not Evaluated species are threatened which is three times greater than currently assessed species (7%). This may indicate that a larger proportion of poorly known squamate species are more likely to be threatened than previously thought. Overall, our findings provide an important resource for the conservation management of Australian squamates by highlighting key traits and missing data, as well as providing a list of Data Deficient and Not Evaluated species that should be prioritized for research.

KEYWORDS
conservation, extinction risk, IUCN red list, lizard, modelling, snake

INTRODUCTION

We are currently in a biodiversity crisis and facing the sixth mass extinction (Barnosky et al., 2011; Ceballos et al., 2020; SCBD, 2020). This biodiversity decline has strong and negative impacts on ecosystem functions (Ceballos et al., 2017; Jaureguiberry et al., 2022). The cause of this decline is primarily due to habitat loss, climate change, invasive species and disease, among other factors (Ceballos et al., 2015; Pörtner et al., 2021). Biodiversity loss

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can be reduced through conservation management which is effectively developed with knowledge of species and the threats they face (Barnosky et al., 2011; Bland et al., 2017; Pörtner et al., 2021; SCBD, 2020). Lacking this knowledge poses a major impediment to effective conservation (Bland et al., 2017; Ceballos et al., 2020; Tingley et al., 2016).

The International Union for Conservation of Nature (IUCN) is a conservation organization that uses data collaborated by experts to assign a species to an extinction risk category in their Red List of threatened species (IUCN, 2021; Mace et al., 2008). These classifications range from not threatened categories (Least Concern, Near Threatened) through to threatened (Vulnerable, Endangered, Critically Endangered) and extinct categories (Extinct in the Wild, Extinct). The Red List is an important tool that helps guide conservation planning and management (Mace et al., 2008; Rodrigues et al., 2006). When there are insufficient data to assign species to one of the above categories species are labelled Data Deficient (IUCN, 2021). Data Deficient species possess several traits that make them more akin to threatened species than to non-threatened ones (Caetano et al., 2022; Gumbs et al., 2020). Species are labelled Not Evaluated when they have yet to be evaluated by the IUCN expert assessments and may possess different traits to assessed species (IUCN, 2021; Meiri & Chapple, 2016). An inability to properly classify species runs the danger of failing to safeguard highly vulnerable species due to minimal protection and funding as a result of their uncertain extinction risk (Bland et al., 2017; Jarić et al., 2016). Thus, without effective conservation actions, some Data Deficient and Not Evaluated species could slip towards extinction unnoticed (Bland et al., 2017; Jarić et al., 2016).

Reptiles, the most diverse group of terrestrial vertebrates (~12 000 species, as of April 2023, with hundreds more species being discovered each year), are the land vertebrate group with the highest number of unassessed species (Bland & Böhm, 2016; Tingley et al., 2019; Uetz et al., 2021). Fifteen per cent of reptile species have not been assigned an extinction risk category by the IUCN, and consequently over 1500 species are likely missing out on important conservation management (Cox et al., 2022; Uetz et al., 2021). It is thus crucial that these species are promptly assigned an extinction risk category, or a predicted category, to ensure that conservation planning and actions can be implemented before it is too late.

Previous studies have found that certain intrinsic traits (i.e. ecological, morphological and life history traits) are associated with extinction risk (Senior et al., 2021; Tingley et al., 2013). Large body size has been found to be associated with reptile extinctions (Slavenko et al., 2016). Perhaps due in part to a slow life history and an associated slow recovery from environmental disturbances (Böhm et al., 2016; Tingley et al., 2013), or because of direct prosecution of large-sized reptiles by humans. Viviparity is also associated with a slow life history as it lowers reproductive frequency (Böhm et al., 2016; Sinervo et al., 2010). Viviparity in squamates is an adaption to cold climates where the rapid effects of climate change place the ecosystems at high risk (Sinervo et al., 2010). Threatened lizards tend to have smaller clutch sizes than not threatened species and low fecundity often increases extinction risk (Siliceo & Díaz, 2010). Recently described species from all vertebrate groups have been found to be at higher extinction risk than species described longer ago (Liu et al., 2022). However, this is likely a proxy of other traits and should be considered in conjunction with other factors (Liu et al., 2022). Additionally, conflicting evidence has suggested that both diurnal and nocturnal species may be more prone to extinction (Meiri & Chapple, 2016; Tingley et al., 2013).

Species with small geographical ranges often have an increased extinction risk (Bland & Böhm, 2016; Böhm et al., 2016; Geyle et al., 2021;

Tingley et al., 2013) and indeed, a small range size features heavily as the reason for assigning a threat category in IUCN reptile assessments, partially due to the IUCN assessment process (Böhm et al., 2016; Chapple et al., 2019; Meiri et al., 2023). A small geographical range often means a small population size, which can lead to a greater risk of demographical stochasticity, inbreeding and localized threats (Tingley et al., 2013). Worldwide, 89% of reptile extinctions have occurred on islands (Slavenko et al., 2016). Likewise, the three extinct or extinct in the wild Australian squamates are endemic to islands, and all island endemic squamates are listed as threatened (largely due to threats from invasive species; Tingley et al., 2019).

Several studies have had great success in predicting the extinction risk of Data Deficient and Not Evaluated species by combining knowledge regarding species' traits into models (Bland, Collen, et al., 2015; Bland, Orme, et al., 2015; Borgelt et al., 2022; Caetano et al., 2022; Soares et al., 2022). Data Deficient and Not Evaluated species have been found to possess traits that differentiate them from assessed species and may lead to unique conservation strategies (Meiri & Chapple, 2016; Tingley et al., 2019). Concerningly, a large proportion of Data Deficient species have been predicted to be threatened compared to evaluated species (Borgelt et al., 2022; Caetano et al., 2022). Identifying potentially threatened species can help direct conservation funds and research for priority species (Howard & Bickford, 2014; Jarić et al., 2016). This allows preventative measures to be put into place for species that may have a high extinction risk before their official IUCN assessment can be completed (Bland & Böhm, 2016; Bland, Orme, et al., 2015; Böhm et al., 2016; Tingley et al., 2013).

We use Australian squamates as a case study because Australia has diverse and distinctive reptile fauna (>95% of species are endemic; Chapple et al., 2019; Geyle et al., 2021). In particular, Australia is a diversity hotspot of squamates (snakes and lizards), possessing approximately 10% of the world's squamates (Roll et al., 2017; Tingley et al., 2019; Uetz et al., 2021). Australian lizards were under-assessed in 2016 by the IUCN assessments due to a rapid rate of discovery and poorly known taxonomy (Meiri & Chapple, 2016) – but substantial assessment work was conducted in 2017 to amend this knowledge gap (Tingley et al., 2016, 2019). However, approximately 10% of Australian squamates still lack sufficient data to be assigned an extinction risk category, and these species are unlikely to receive sufficient conservation management prior to their official assessment (Chapple et al., 2019, 2021; Tingley et al., 2019). Global geographical extinction risk skew has been found with Data Deficient and threatened reptile species which commonly inhabit the tropics and Oceania (Böhm et al., 2013; Tonini et al., 2016). Additionally, reptile extinction risk has been found to be varied across taxa, as Geoemydidae, Crocodylidae, Pygopodidae and Xantusiidae are some of the most threatened reptile families (Böhm et al., 2013; Tolley et al., 2016). However, this was not the case for Australian squamates, where all major taxa are equally at risk (Tingley et al., 2019). Due to this historic knowledge gap, and the uniqueness and diversity of Australian reptiles, it is valuable to complete a focused local analysis that will provide specific and relevant insight for conservation management (Evans et al., 2011; Geyle et al., 2021; Tingley et al., 2019).

Here we determine why Australian squamates are listed as Data Deficient, and how traits compare between IUCN conservation status categories for all Australian squamates. We predict that Data Deficient and Not Evaluated species will have similar traits to threatened species (i.e. have a small range, recent description, large body mass, small clutch size and more likely to be insular endemic, known only from the type locality, viviparous, fossorial, reduced-limbed or limbless and nocturnal; Bland & Böhm, 2016; Caetano et al., 2022). In addition, we use a recently published

machine learning model for reptiles (Caetano et al., 2022) to predict individual species' extinction risk and to help identify potentially threatened species. This method can prioritize and direct research and conservation management in a cost-effective way prior to comprehensive data collection and expert assessment (Böhm et al., 2016; Borgelt et al., 2022; Jarić et al., 2016).

MATERIALS AND METHODS

Dataset

The IUCN Red List experts conducted comprehensive Australian squamate assessment workshops in 2017 (Chapple et al., 2019; Tingley et al., 2019), classifying 43 of the ~960 assessed squamate species as Data Deficient. However, since mid-2017 there has been substantial taxonomic activity, resulting in the description of 78 new species (as of March 2021). These new species have not been assessed against IUCN Red List criteria and thus Not Evaluated. Using IUCN Red List assessments, we identified four key reasons why species were classified as Data Deficient, and we assigned Data Deficient species to at least one of these four categories: Uncertain Intrinsic traits (uncertain life history or ecology); Uncertain drivers of threat (uncertain threats or impacts of threats); Uncertain Distribution (difficult to survey habitat, single specimen, not found in recent surveys, fragmented population, restricted range); and Uncertain Taxonomy (single specimen, unknown conspecific; see Table S1 for further definitions and Table S2 for examples). Uncertain drivers of threat were the leading cause of Data Deficient categorization of Australian squamates by the IUCN Red List, followed by uncertain distribution (Figure 1). Uncertain intrinsic traits and taxonomy were less common causes. Four Data Deficient species (9.3%) were categorized due to one reason, 16 species (37.2%) due to two reasons, 16 species (37.2%) due to three reasons and seven species (16.3%) due to all four reasons.

We collated a dataset of current Data Deficient and Not Evaluated Australian squamate species, using trait data from Meiri (2018) (and subsequent updates), and distributional data from Roll et al. (2017) and their update by Caetano et al. (2022). We updated the trait data using the primary literature, and the taxonomy using the reptile database (Uetz et al., 2021). Marine species were excluded as they have different characteristics and face different threats to terrestrial species (Böhm et al., 2013). We compared the 43 Data Deficient species and 78 Not Evaluated species (a total

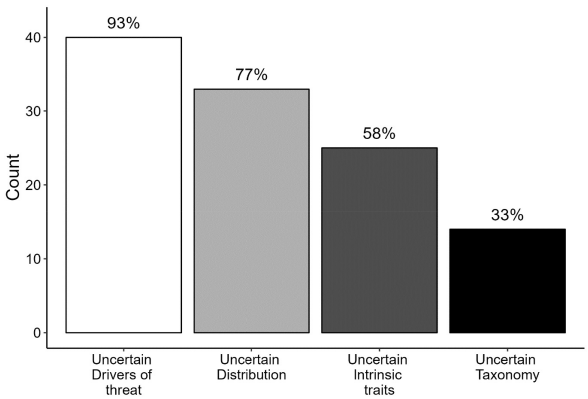

FIGURE 1 The four key justifications for data deficiency classification by the IUCN Red List amongst Australian squamates, with the percentage of Data Deficient species within each category. Note, species may be assigned to more than one justification category.

of 121 species) to the 903 extant Australian squamates with threat assessments (an overall total of 1024 species).

The dataset contained key traits for each species: Conservation status (Data Deficient, Not Evaluated, not threatened and threatened); geographical range size (in km^2, log transformed; Böhm et al., 2016); body mass (derived from snout-vent length, log transformed; Böhm et al., 2016); reproductive mode (oviparous, viviparous or mixed; Sinervo et al., 2010); insular endemism (landmasses with ranges smaller than Australia; Slavenko et al., 2016); clutch size (adjusted for mass, log transformed; Siliceo & Díaz, 2010); substrate mode (aquatic, fossorial, or surface active; Meiri & Chapple, 2016); leg development (fully limbed, limbless or limb reduced; Meiri & Chapple, 2016); year of description (Meiri, 2016); activity phase (cathemeral, diurnal or nocturnal; Tingley et al., 2013); and whether the species is known only from its type locality (Meiri et al., 2018). These traits were chosen due to their success in previous studies on predicting extinction risk (Meiri & Chapple, 2016; Tingley et al., 2013, 2019).

Statistical analysis

For each Data Deficient species, we identified the key reason(s) for being placed in the data-deficient category based on the IUCN Red List justification and compiled a graph of the key reasons for visual comparison.

Univariate analysis

To examine the relationship between conservation status and individual categorical traits, we used a chi-square test and post-hoc analysis. To analyse the relationship between conservation status and individual numerical traits, we used a Kruskal–Wallis rank sum test and a Dunn's test with a Bonferroni adjustment. Assumptions were checked visually and were met (Figure S1). There was a large proportion of unavailable values for clutch size (35%), reproductive mode (18%), activity phase (16%) and substrate use (9%). All remaining traits had less than 3% unavailable values. The null hypothesis that there was no relationship between the trait and the conservation status was rejected if $p < 0.05$.

Multivariate analysis

We then explored the distribution of species in a multivariate trait space. We conducted a factor analysis of mixed data to examine correlations amongst conservation statuses and mixed categorical and numerical traits with <10% missing values. Dimensions one and two were selected by the Kaiser–Guttman criterion (eigenvalue > 1; Jackson, 1993). Quantitative and qualitative variables were plotted on these dimensions separately. Individual species classified by conservation status were also plotted on dimensions one and two. We additionally modelled the relationship between conservation status as the response variable and the combined effects of all traits with <10% missing values as the predictor variables by fitting a binomial generalized linear model with a logit link function and calculating variable importance and McFadden's R^2.

Analysis was undertaken using R (version 4.0.4; R Core Team, 2021) and packages chisq.posthoc.test (version 0.1.2; Ebbert, 2019), dunn. test (version 1.3.5; Dinno, 2017), FactoMineR (version 2.8; Le et al., 2008) factoextra (version 1.0.7; Kassambara & Mundt, 2020), caret (version 6.0.94;

Kuhn, 2008), pscl (version 1.5.5.1; Jackman, 2020) and xgboost (version 0.90; Chen et al., 2019).

Predicting extinction risk for Australian squamates

To predict the extinction risk of Data Deficient, Not Evaluated and assessed Australian squamate species, we used a recently published machine learning model trained on global reptile data (Caetano et al., 2022). XGBoost is a versatile and robust machine learning algorithm which was used to predict the extinction risk of Australian squamates (Caetano et al., 2022). The model's parameters include climate (76 features), human encroachment (45 features), biogeography (26 features), topography (9 features) and ecosystem productivity (8 features); additionally, species-level data (including body mass and insularity), spatial and phylogenetic autocorrelation and range size. These intrinsic and extrinsic features are included due to their importance in predicting extinction risk and high data availability (Caetano et al., 2022). All 43 Data Deficient, 78 Not Evaluated and 903 assessed Australian squamate species (total 1024 species) were assigned a predicted IUCN extinction risk by our model. This includes an additional 33 species (27 NE and 6 LC) which were not predicted in Caetano et al.'s (2022) study due to unavailable data and were analysed here using their methods. We evaluated classification metrics to determine the model's accuracy, performance and agreement between predictions and actual classifications for assessed species using a confusion matrix (Tables S3 and S4).

RESULTS

How do traits compare between IUCN conservation status categories?

Univariate analysis

Not threatened species have larger ranges than Data Deficient, Not Evaluated and threatened species ($\chi^2 = 201.05$, df = 3, $p < 0.001$; Table S5, Figure 2a). Larger proportions of Data Deficient and threatened species are insular endemic, while not threatened species are more continental ($\chi^2 = 64.76$, df = 3, $p < 0.001$; Table S6, Figure 3a). Data Deficient, Not Evaluated and threatened categories have larger proportions of species known only from their type locality than not threatened species ($\chi^2 = 173.70$, df = 3, $p < 0.001$; Table S7, Figure 3b). The median year of description was similar for Data Deficient species (1991) and threatened species (1985), while not evaluated were described more recently (2018), and not threatened species substantially earlier (1968; $\chi^2 = 179.65$, df = 3, $p < 0.001$; Table S8, Figure 2b).

Not evaluated species have a smaller body mass ($\chi^2 = 13.46$, df = 3, $p < 0.001$; Table S9, Figure 2c) and clutch size ($\chi^2 = 9.66$, df = 3, $p = 0.022$; Table S10, Figure 2d) than those of Data-Deficient and not threatened species, while the other conservation status categories all had similar body mass and clutch sizes. There are significantly more threatened viviparous species than the other conservation status categories which all share similar proportions of reproductive modes ($\chi^2 = 17.50$, df = 6, $p = 0.008$; Table S11, Figure 3c).

Not Evaluated species are more likely to be surface active ($\chi^2 = 26.55$, df = 6, $p < 0.001$; Table S12, Figure 3d) and possess well-developed legs ($\chi^2 = 20.87$, df = 6, $p = 0.002$; Table S13, Figure 3e) than the other conservation status categories which share similar proportions of substrate and

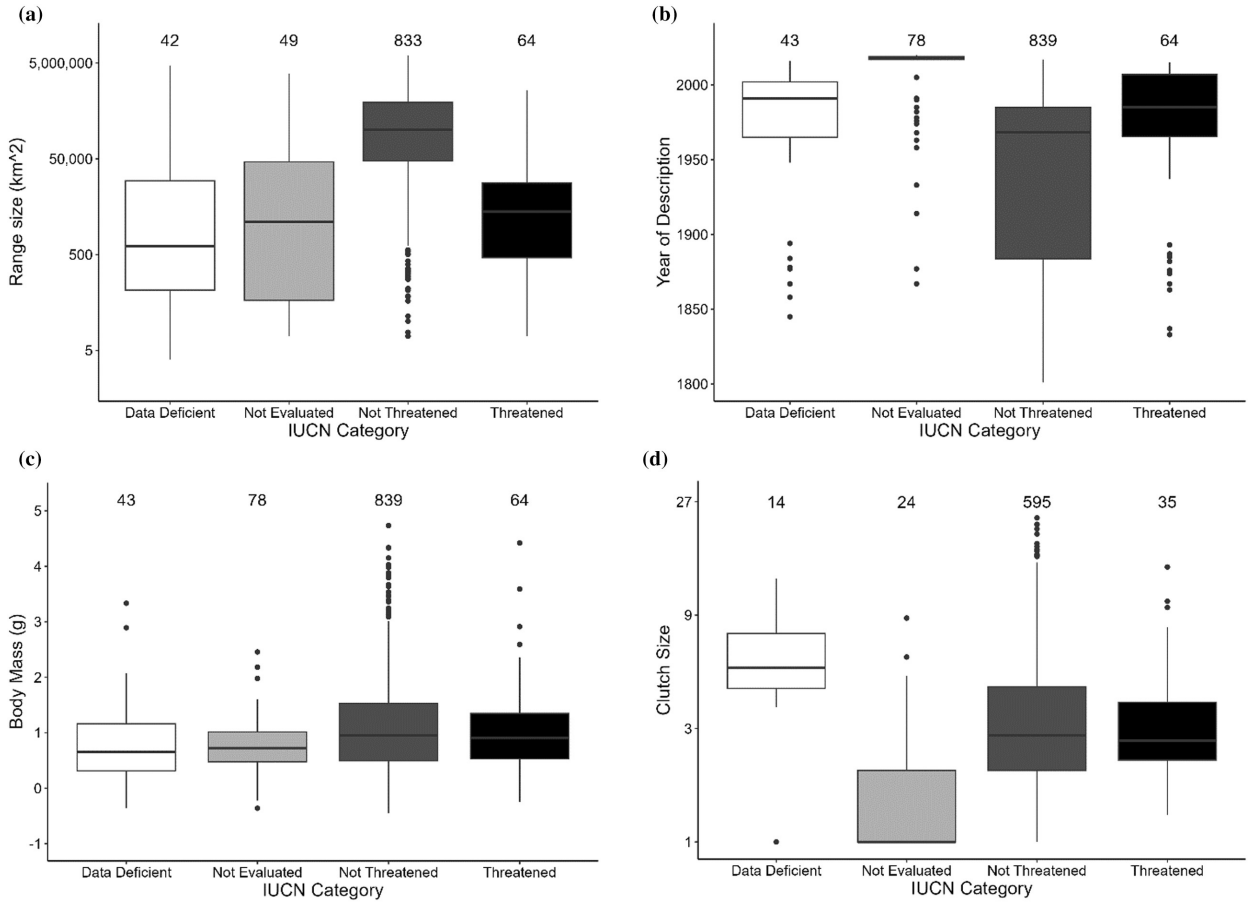

FIGURE 2 Boxplots of Australian squamate traits for each IUCN conservation status category, with sample size: (a) range size (in km^2); (b) year of description; (c) body mass (log transformed, in g); (d) clutch size.

limbed species. We found activity phase has a non-significant relationship with conservation status ($\chi^2 = 9.17$, df = 6, $p = 0.165$; Figure 3f).

Multivariate analysis

The factor analysis of mixed data dimensions represents an association among the qualitative and quantitative intrinsic traits. Traits that are clustered are likely to be correlated while those at larger angles are likely to not be correlated and those opposite are likely to be negatively correlated. Dimensions one and two of our factor analysis of mixed data did not represent a large proportion of variance for Australian squamates. However, our analysis did reveal that Data Deficient and threatened species share a similar cluster profile (Figure 4). Data Deficient and threatened species had a positive association with insular endemism and known only from the type locality and a negative association with mass and range. Not Evaluated species had a distinct profile and were strongly and positively associated with year of description. Not threatened species were not strongly associated with dimensions 1 and 2, but were associated with non-insularity, wide ranging, surface activity and full limb development. Not threatened species were also positively associated with range and mass and negatively associated with year of description. The generalized linear models reached similar associations amongst traits and conservation status (McFadden's R^2: data deficient 0.250, not evaluated 0.376, threatened 0.210, not threatened 0.319; Tables S14–S17).

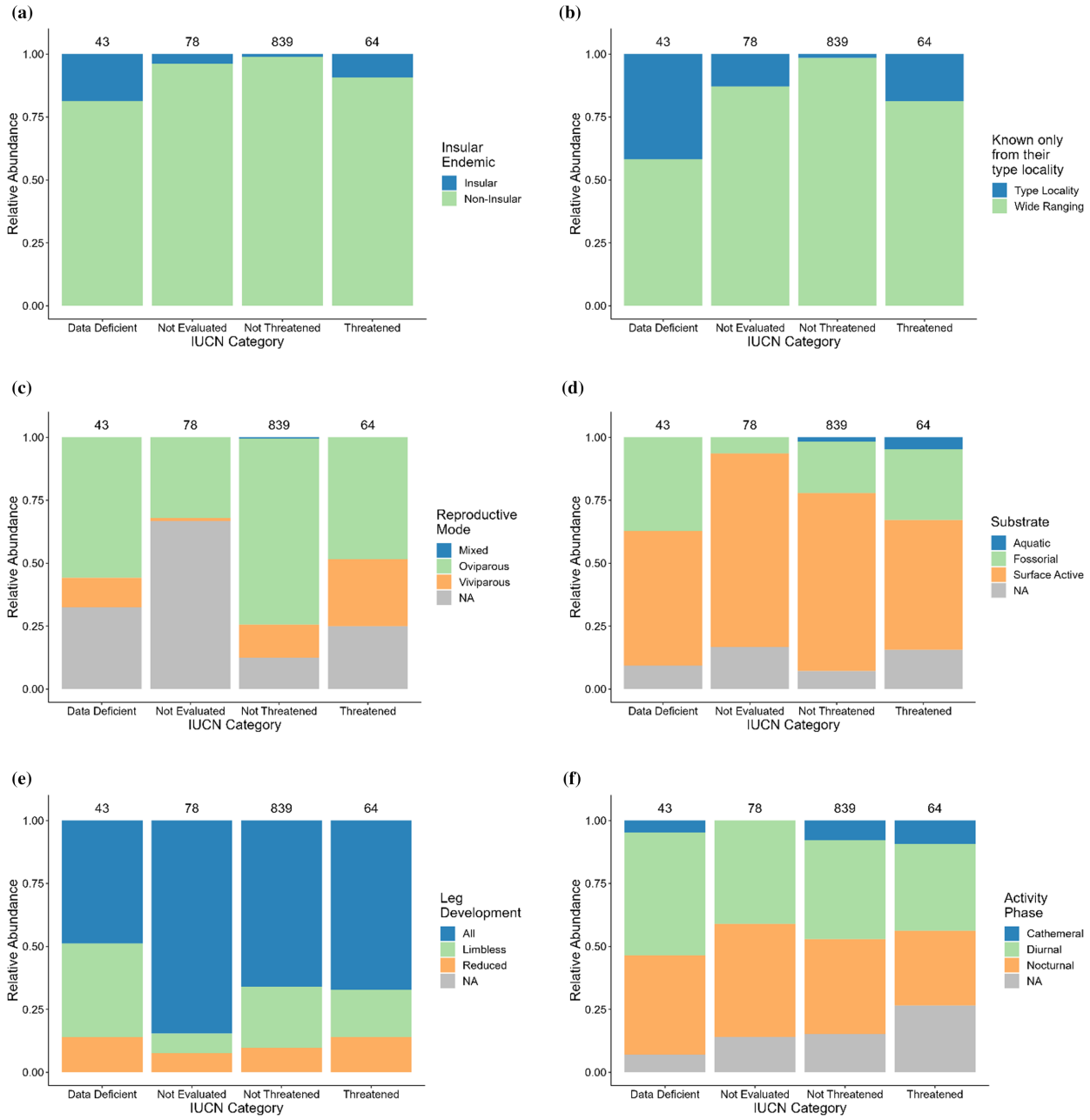

FIGURE 3 Percentage stacked bar graphs of Australian squamate traits for each IUCN conservation status category, with sample size: (a) Insular Endemic; (b) Known only from the type locality; (c) Reproductive mode; (d) Substrate; (e) Leg development; (f) Activity phase.

Predicting extinction risk for Australian squamates

We predicted an extinction risk category for all 1024 Australia squamate species (Table S18). The model correctly assigned 896 of the 903 (99.2% accuracy) previously assessed species to a dichotomous threatened or not threatened status, and 881 (97.6% accuracy) species' correctly to their specific extinction risk categories. For specific extinction risk categories, the model had a high average precision (90.5%), sensitivity (76.5%), specificity (97.3%) and F1-score (80.5%; Table 1) and a kappa statistic of 0.85. Of the 22 species that were predicted to have a different specific extinction risk category (Table S19) than currently assigned, six (27.3%) are predicted to be more at risk than currently assigned and 16 (72.7%) are predicted to be less at risk than currently assigned.

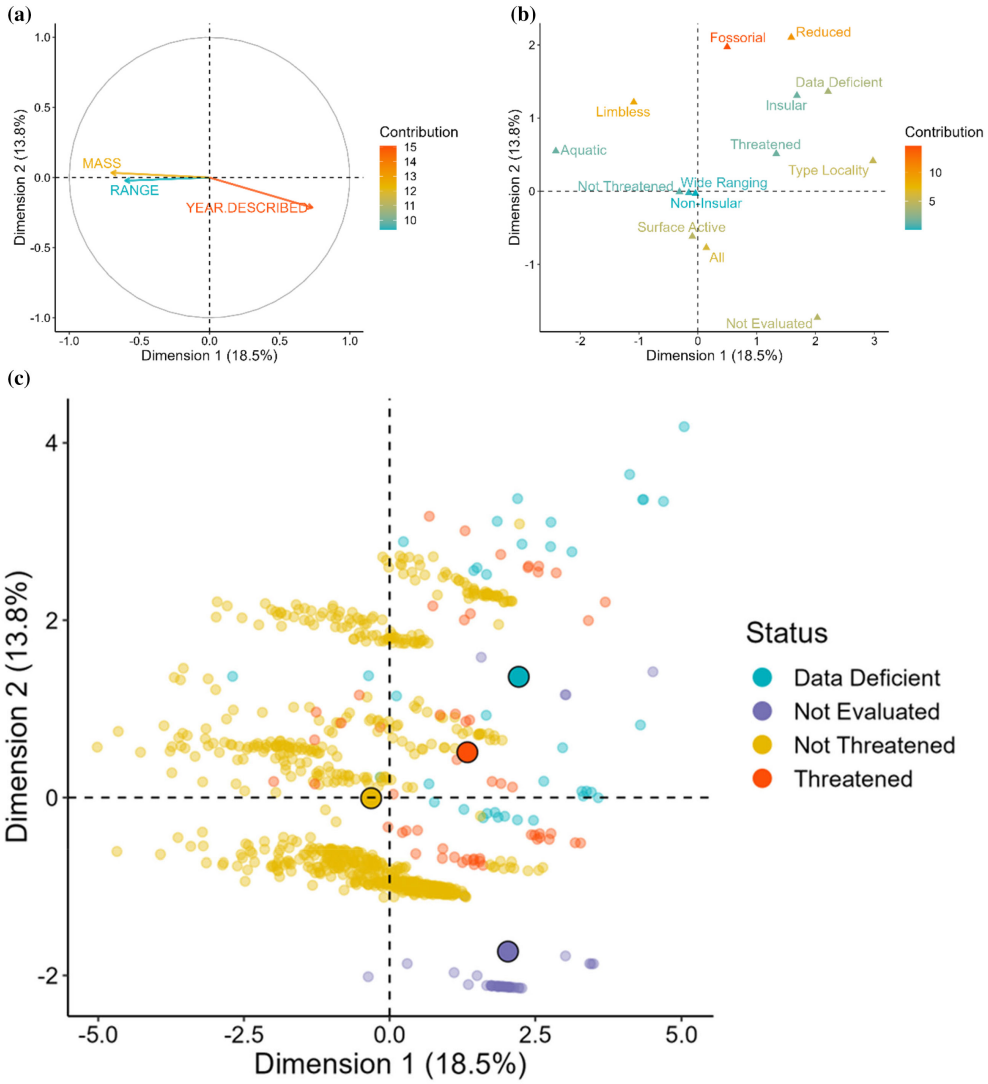

FIGURE 4 The factor analysis of mixed data for traits with <10% missing values: (a) The relationship among quantitative variables and dimensions one and two per their contribution to the dimensions; (b) The relationship amongst qualitative variables and dimensions one and two per their contribution to the dimensions; (c) The relationship among individual species (small symbols) coloured by conservation status on dimensions one and two with the conservation status mean (larger symbol).

TABLE 1 Accuracy metrics of automated assessment model classifying previously assessed Australian squamates into IUCN extinction risk categories and an average: Precision (fraction of correct predictions for a category), sensitivity (fraction of a category that were correctly predicted), specificity (fraction of true negatives) and F1 (weighted mean of precision and sensitivity).

Extinction risk category	Precision	Sensitivity	Specificity	F1
LC	0.99	>0.99	0.88	0.99
NT	0.87	0.68	>0.99	0.76
VU	0.92	0.82	>0.99	0.87
EN	0.75	0.92	0.99	0.83
CR	1.00	0.40	1.00	0.57
Average	0.91	0.77	0.97	0.81

One hundred twenty-one Data Deficient and Not Evaluated species were predicted to an IUCN extinction risk category. Of these, 95 (78.5%) were assigned to a not threatened category (91 as LC and 4 as NT) and 26

(21.5%) were assigned to a threatened category (12 as VU, 8 as EN and 6 as CR; Table S20). These proportions remain similar for Data Deficient (79.1% not threatened, 20.9% threatened) and Not Evaluated species (78.2% not threatened, 21.8% threatened) separately. Of the 903 already assessed species, 842 (93.2%) were assigned to a not threatened category (827 as LC and 15 as NT) and 61 (6.8%) were assigned to a threatened category (25 as VU, 32 as EN and 4 as CR).

DISCUSSION

Australia has a poor track record when it comes to biodiversity loss (Geyle et al., 2018). Species' predicted extinction risk can be valuable for government and conservation organizations to identify potentially threatened species and direct conservation actions to reduce further extinctions (Jarić et al., 2016; Mace et al., 2008). We found that data deficiency was often applied to Australian squamates when they lacked threat and/or distribution data. Concerningly, Data Deficient and Not Evaluated species tend to possess traits that resemble those of threatened species, including small range size (often being known only from the type locality), insular endemism and being recently described. Not Evaluated species are inclined towards distinct traits, including smaller body mass and clutch size, and are more likely to be surface active and have four well-developed legs than evaluated species. Our model correctly predicted the extinction risk for most assessed species. Concerningly, one-fifth of Data Deficient and Not Evaluated species are predicted to be threatened, which is three times greater than currently assessed species.

Why were Australian squamate species listed as Data Deficient?

The leading justifications of Australian squamate data deficiency were similar to that of global reptile data deficiency which included unknown threats, population status and distribution (Figure 1; Bland et al., 2017). Likewise, uncertain distribution is a key justification of data deficiency in other taxa, such as mammals and amphibians (Bland et al., 2017; Bland, Collen, et al., 2015). Uncertain taxonomy was another major rationale for data deficiency in mammals and amphibians, which was the least cited justification in our data perhaps due to the substantial assessment work conducted in 2017 (Bland et al., 2017; Bland, Collen, et al., 2015; Tingley et al., 2019). Moreover, cryptic and misidentified specimens in collections can impact data and management in poorly studied taxonomic groups. Consistent with other taxa, the majority (91%) of Australian squamates were categorized as Data Deficient due to multiple reasons which suggests that these species possess a broad knowledge gap (Bland, Collen, et al., 2015; Bland, Orme, et al., 2015).

Incomplete distribution information is cited for over 75% of Data Deficient Australia squamate species. This may influence their ability to be correctly assigned an extinction risk categorization as the majority of assessed Australian squamates were assigned to near threatened or a threatened category based primarily on their restricted geographical range (Criterion B or Criterion D2; Tingley et al., 2019). Lacking knowledge of the threats that Data Deficient species face is also a major knowledge gap, which makes it difficult to implement appropriate protective conservation strategies (Bland & Böhm, 2016). Thus, in the case of Australian squamates, future research effort should be seriously invested in identifying species' distribution and

threats. In particular, intensive field studies will be beneficial in establishing species' threats and distributions, for instance, Graham et al. (2023).

How do traits compare between IUCN conservation status categories?

Half of the traits we examined (5 out of 10) are associated with increased extinction risk in Australian squamates, which aligns with previous studies on reptiles and other terrestrial vertebrates. Small range sizes are frequently associated with an increased extinction risk and likewise threatened Australian squamate species have smaller range sizes than not threatened species (Böhm et al., 2016; Senior et al., 2021; Tingley et al., 2019). Indeed, restricted range size is an IUCN Red List criterion (Criterion B or Criterion D2), and consequently, it is unsurprising that this trait is linked with threatened species (IUCN, 2021; Tingley et al., 2019). A small range size is often associated with a small population size, which increases a population's susceptibility to inbreeding and localized threats which will additionally increase a species' extinction risk (Senior et al., 2021; Tingley et al., 2013). Indeed, Data Deficient and Not Evaluated species may have their range size initially underestimated due to them lacking distributional data and thus their extinction risk may transform as more data are collected (Bland et al., 2017; Bland & Böhm, 2016). Small ranges of evaluated Australian squamates (Senior et al., 2021), and Not Evaluated lizards (Meiri & Chapple, 2016), have been linked with habitat loss and accordingly an increased extinction risk. This is concerning because it suggests that many Data Deficient and Not Evaluated species may be at risk of a threatened categorization due to having a very small geographical range and the indirect threats associated with it.

Nearly 90% of reptile extinctions worldwide and all lizard extinctions in Australia have occurred on islands (Slavenko et al., 2016; Tingley et al., 2019). We confirmed that insular endemism is linked to higher extinction risk in Australian squamates (Senior et al., 2021). Island species are disproportionately affected by invasive species, and tend to have larger body sizes than mainland relatives which itself is associated with a higher extinction risk (Bland & Böhm, 2016; Senior et al., 2021; Tingley et al., 2019). Unsurprisingly, Data Deficient, Not Evaluated and threatened species have a large proportion of species known only from their type localities. Species known only from their type locality have, by definition, extremely small ranges, and are often threatened with extinction (Bland & Böhm, 2016; Meiri et al., 2018). They also often possess traits that make them difficult to locate, such as a small body size, a recent description and nocturnality (Meiri et al., 2018). A large proportion of recently described lizards are nocturnal which has been linked to higher extinction risk due to competition from invasive species (Meiri, 2016; Meiri & Chapple, 2016). However, other research suggests diurnal species are more prone to extinction due to human interactions (Tingley et al., 2013). The activity phase does not differentiate amongst conservation status in our models for Australian squamates. This may be partially due to incomplete or missing activity data for a large number of species as is common in reptile research (Meiri, 2016; Meiri & Chapple, 2016).

Large-bodied species are commonly threatened with extinction because they often require large home ranges and possess related threatened traits, such as low population density and a slow life history (Böhm et al., 2016; Cardillo et al., 2005; Tingley et al., 2013). A slow life history prevents a species from responding to rapidly changing environments and threats and thus contributes to an increased extinction risk (Rowe, 2008).

Additionally, extinction risk may increase for large species because they require large home ranges which are often fragmented and degraded by humans (Cardillo et al., 2005). Unlike other taxa and reptiles globally (Böhm et al., 2016; Cardillo et al., 2005; Marcel et al., 2005), we found no evidence that body mass was linked to extinction risk in Australian squamates. Larger body sizes are associated with larger clutch sizes in lizards and thus, it is unsurprising these traits draw similar conclusions (Meiri et al., 2020; Meiri & Chapple, 2016). Approximately only a third of Data Deficient and Not Evaluated Australian squamate species have clutch size data, which may influence our results. Nevertheless, Not Evaluated Australian squamates have smaller clutch and body sizes than evaluated species which is expected because of the relationship between these two traits (Meiri et al., 2020; Reed & Shine, 2002). Small clutch size is a predictor of a threatened extinction risk for mainland (Siliceo & Díaz, 2010) and insular endemic (Novosolov et al., 2013) lizards and thus, is concerning for Not Evaluated Australian squamate species.

Reproductive mode has a large proportion of missing data, including over half of Not Evaluated species missing information for this trait. Due to this knowledge gap in Data Deficient and Not Evaluated species, it remains unclear if they are inclined towards a particular reproductive mode. Nevertheless, we found a substantial proportion of viviparous species are threatened. Our results align with research that found viviparous species were twice as likely to be threatened with extinction as oviparous species (Sinervo et al., 2010). Similar to a large body size, viviparity is associated with a slow life history (i.e. less frequent reproduction) and has been weakly linked to threatened extinction risk in Australian squamates (Senior et al., 2021). Additionally, viviparity is posited to be a cold climate adaptation (Zimin et al., 2022) and thus species often have a restricted, high elevation range and inhabit areas where climate change is having a rapid impact (Senior et al., 2021; Sinervo et al., 2010). Cold climates are often subjected to a sizable human footprint in Australia which negatively impacts species due to an association with habitat loss, overexploitation and invasive species (Senior et al., 2021). These cool climate habitats are more susceptible to human influence and climate change, of which their threatening impacts will only continue to grow in the future (Sinervo et al., 2010).

Leg development is associated with substrate use, and this was likewise found in Australian squamates (Camaiti et al., 2021; Meiri, 2016). Unsurprisingly, Not Evaluated Australian squamate species share traits similar to recently described lizards which are more likely to be surface active with well-developed limbs (Meiri, 2016). Previous research suggests a bias towards the assessment of species that are easier to observe and study which may partially explain the association of these traits with Not Evaluated and recently described species (Meiri & Chapple, 2016).

The variance explained in our factor analysis of mixed data suggests that our model has a complex dataset and relationships between traits. Nevertheless, Data Deficient and threatened species share similar cluster profiles which suggest they have a similar relationship with the traits. These species closely align with insular endemism, known only from the type locality and a smaller range size which are all traits that are often associated with increased extinction risk (Slavenko et al., 2016; Tingley et al., 2019). Unsurprisingly, not threatened species were surface active with well-developed limbs and were associated with continentality, wide ranging (known from more than the type locality), large ranges and large masses. Additionally, as by definition, Not Evaluated species were most strongly associated with year of description (Meiri & Chapple, 2016). Overall, these profiles came to similar conclusions of traits' associations with conservation status as the single trait and generalized linear models.

The generalized linear models are similarly providing information on the associations between the traits, but of a binomial relationship for each conservation status. Thus, this analysis is unable to compare all of the conservation statuses at once which may influence the traits' relationships and explain some of the variation between the generalized linear models and the factor analysis of mixed data.

Extinction risk predictions of Australian squamates

Our model was able to predict the extinction risk of assessed species very accurately, which suggests that it is a useful tool for temporarily assessing Australian squamates. This supports growing research that finds modelling extinction risk to be very successful (Bland & Böhm, 2016; Bland, Orme, et al., 2015; Borgelt et al., 2022; Caetano et al., 2022). It is vital that regional studies are conducted in order to address unique threats and conditions to a region that would be overlooked in a global analysis (Borgelt et al., 2022; Geyle et al., 2021; Roll et al., 2017; Tingley et al., 2019). Twenty-two per cent of Data Deficient and Not Evaluated species were predicted to be threatened, which is similar to previous models' predictions for Data Deficient reptiles globally (Bland & Böhm, 2016; Caetano et al., 2022). Although, a model for reptiles from terrestrial, freshwater and marine environments has predicted as many as 59% of Data Deficient species may be threatened with extinction (Borgelt et al., 2022). The proportion of Data Deficient and Not Evaluated species predicted to be threatened is three times current assessment proportions, with only 7% of assessed Australian squamates classified as threatened. Overall, this supports growing evidence that Data Deficient species of all taxa are more likely to be threatened than currently assessed species (Bland, Collen, et al., 2015; Borgelt et al., 2022; Caetano et al., 2022; Howard & Bickford, 2014).

Our model suggests a small proportion of currently assessed species may decrease their extinction risk category with an updated assessment. Indeed, a review of predictive models found that a majority of least concerned species can be correctly predicted, but Near Threatened and threatened categories were commonly incorrectly predicted to be Least Concern (Di Marco, 2022). For instance, *Liopholis montana*, which is currently listed as Near Threatened by the IUCN (2022), was predicted to be Least Concern by our model. However, a recent expert assessment (using IUCN criteria) list *L. montana* as Endangered (Department of the Environment, 2023c). This assessment was made based on a restricted range and declining habitat (Department of the Environment, 2023c). A discrepancy in geographical range size between IUCN assessments and our model, as well as an inability of the model to qualify the impact of threats may lead to this mismatch in extinction risk assessments (Di Marco, 2022). Thus, official assessments by experts, which can incorporate more complex, relevant information are important for threatened species (Di Marco, 2022).

Importantly, using our model, we are able to predict species that may be threatened and thus, prioritize these species by conservation managers for data collection and reassessment, which may shape conservation strategies (Bland & Böhm, 2016; Jarić et al., 2016). For instance, our model predicted that the Data Deficient *Lampropholis elongata* be classified as Endangered, and indeed, recent research has meant that it has recently been listed as Critically Endangered (Department of the Environment, 2023b; Graham et al., 2023). Our model correctly predicted this species to be threatened and therefore a high priority for research, which was supported by expert assessment. Additionally, the Not Evaluated *Egernia roomi* was predicted to be Endangered by our model and recent expert assessment

(using IUCN criteria) has listed it as Critically Endangered (Department of the Environment, 2023a). Again, our model correctly predicted that this species was threatened, and expert assessment was able to integrate complex aspects of range and declining habitat to provide a detailed assessment (Department of the Environment, 2023a). The data gathered for these expert assessments will be instrumental in establishing specialized conservation management for these species (Cazalis et al., 2022; Jarić et al., 2016).

FUTURE DIRECTIONS & CONCLUSIONS

We showed that species are assigned to the Data Deficient category for common reasons and that particular traits are associated with extinction risk in Australian squamates. Our model predicts six Australian squamates to be more threatened than previously assessed. It further predicts 26 Data Deficient and Not Evaluated species to be threatened. These 32 species should be research priorities to ensure that an accurate extinction risk classification can be determined, and effective conservation strategies can be developed where necessary. In line with research by Chapple et al. (2021), we recommend key pieces of information are collected to enable the rapid assessment of species. These should include range size and the number of populations, threats and habitat preferences (Chapple et al., 2021).

Geographical range size is a strong predictor of extinction risk in many models, including ours, and features as a criterion to allow classification of threat under IUCN criterion B, which can have its shortcomings if other variables are not interacting in determining the extinction risk (Bland & Böhm, 2016; Bland, Collen, et al., 2015; Caetano et al., 2022). Indeed, differences in the ranges used by Caetano et al. (2022; GARD ranges) for their test dataset, and those used by the IUCN to assess the same species are likely responsible for much of the differences between the modelled and actual assessments (Di Marco, 2022). Additionally, running the model using only Australian species, rather than a global dataset may provide more specific results by incorporating geographical uniqueness of Australia and may be able to investigate residual phylogenetic signal. Lack of knowledge or inaccurate data (i.e. underestimating geographical range size, unknown invasive species and climate change impacts) of Data Deficient and Not Evaluated species will influence the model results (Di Marco, 2022). Consequently, the predicted extinction risk may transform as more data are collected (Jarić et al., 2016). Thus, modelled assessments should only be used as a starting point to direct conservation management and research to priority species (Bland & Böhm, 2016; Caetano et al., 2022; Di Marco, 2022; Jarić et al., 2016). Iterative research and modelling are essential as novel species are described, and our understanding of geographical ranges is refined, because they provide an important resource for both modelled and IUCN assessments, and are unequivocally valuable for conservation.

AUTHOR CONTRIBUTIONS

Lucy Rose Wotherspoon: Conceptualization (equal); data curation (lead); formal analysis (lead); methodology (lead); writing – original draft (lead). **Gabriel Caetano:** Formal analysis (equal); writing – review and editing (supporting). **Uri Roll:** Data curation (supporting); formal analysis (supporting); writing – review and editing (supporting). **Shai Meiri:** Data curation (equal); formal analysis (supporting); writing – review and editing (supporting). **Arman Pili:** Formal analysis (supporting); writing – review and editing (supporting). **Reid Tingley:** Data curation (supporting); formal analysis

(supporting); supervision (equal); writing – review and editing (supporting). **David G. Chapple:** Conceptualization (equal); funding acquisition (lead); methodology (equal); supervision (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data and code associated with this study have been deposited on the Bridges online data repository https://doi.org/10.26180/21116053.v2.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.