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Reptiles on the brink: identifying the Australian terrestrial snake and lizard species most at risk of extinction

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Abstract. Australia hosts approximately 10% of the world's reptile species, the largest number of any country. Despite this and evidence of widespread decline, the first comprehensive assessment of the conservation status of Australian terrestrial squamates (snakes and lizards) was undertaken only recently. Here we apply structured expert elicitation to the 60 species assessed to be in the highest IUCN threat categories to estimate their probability of extinction by 2040. We also assessed the probability of successful reintroduction for two Extinct in the Wild (EW) Christmas Island species with trial reintroductions underway. Collation and analysis of expert opinion indicated that six species are at high risk (>50%) of becoming extinct within the next 20 years, and up to 11 species could be lost within this timeframe unless management improves. The consensus among experts was that neither of the EW species were likely to persist outside of small fenced areas without a significant increase in resources for intense threat management. The 20 most imperilled species are all restricted in range, with three occurring only on islands. The others are endemic to a single state, with 55% occurring in Queensland. Invasive species (notably weeds and introduced predators) were the most prevalent threats, followed by agriculture, natural system modifications (primarily fire) and climate change. Increased resourcing and management intervention are urgently needed to avert the impending extinction of Australia's imperilled terrestrial reptiles.

Additional keywords: anthropogenic mass extinction crisis, Australia, biodiversity conservation, Delphi, expert elicitation, IDEA, lizard, reptile, snake, squamate, terrestrial, threatening processes.

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Introduction

The rate of ecological change is escalating as human impacts become more pervasive and intensive, and consequently, much of the world's biodiversity has suffered marked declines (Johnson *et al.* 2017). A recent review by the United Nations estimated that up to one million species are threatened by extinction as a result of human impacts (IPBES 2019), with Australia having one of the worst track records globally for recent biodiversity loss (Ritchie *et al.* 2013). Along with signatories to the Convention on Biological Diversity, the Australian government has committed to avoiding further extinctions (United Nations 2015; Department of Environment and Energy 2016), a task that first requires identification of the species at most immediate risk. Typically, this is achieved using threatened species lists, such as the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. While the IUCN Red List has been instrumental for establishing global conservation priorities (Rodrigues *et al.* 2006), it is not designed to distinguish species on a rapid trajectory towards extinction from those with very small populations that may persist for long periods (Geyle *et al.* 2018). This is because the threat categories conflate declining populations with small populations, so that counts of threatened species in a given category do not always translate directly into extinction risk (Dirzo *et al.* 2014). It is also far from comprehensive: about a quarter of recognised terrestrial vertebrate species have not been evaluated against IUCN Red List criteria (Tingley *et al.* 2019), and in many cases, existing assessments are out of date.

Consequently, recognised IUCN conservation status (i.e. Critically Endangered, Endangered or Vulnerable) may not be the most sensitive means to identify priorities for halting further extinctions. Indeed, the Christmas Island forest skink (*Emoia nativitatis*) – the only documented extinction of an Australia squamate to date – became extinct in the wild before it was assigned any conservation status, and the few captive individuals died soon after it was listed as Critically Endangered in 2010 (Woinarski *et al.* 2017). The long interval between the demonstration of a significant decline in this species (Cogger and Sadlier 1999) and its listing as threatened meant that it was not afforded any particular priority for research or conservation management until it was far too late (Woinarski *et al.* 2017). Similarly, for two other endemic Christmas Island species that currently exist only in captivity, the blue-tailed skink (*Cryptoblepharus egeriae*) and Lister's gecko (*Lepidodactylus listeri*), there was either no formal assessment of conservation status (blue-tailed skink), or the status was outdated (Lister's gecko), prior to their extinction in the wild (in 2010 and 2012 respectively). It is possible that more Australian reptiles may follow a similar trajectory, given the general susceptibility of reptiles to climate change (Kearney *et al.* 2009; Sinervo *et al.* 2010), and the fact that species that are highly vulnerable to climate change impacts do not always overlap in range with species that have been assessed as threatened (Böhm *et al.* 2016*a*; Meng *et al.* 2016).

Australia is a hotspot for reptile diversity, hosting the largest number of species of any country in the world, and approximately 10% of all known species globally (Tingley *et al.* 2019). The Australian reptile fauna is very distinctive (>90% of species are endemic) (Chapman 2009), but poorly resolved, in part due to the existence of many cryptic lineages (Donnellan *et al.* 1993; Oliver *et al.* 2009). By global standards, there is a very high ongoing rate of description of new species, many of which have traits that make them susceptible to extinction (Meiri 2016). For example, a recent taxonomic review of a wide-ranging agamid species (genus *Tympanocryptis*) resulted in formal recognition of several species with very restricted ranges, including one species that may already be extinct (Melville *et al.* 2019).

Despite mounting evidence of ongoing global declines of reptile species (Gibbons *et al.* 2000; Huey *et al.* 2010; Tingley *et al.* 2016), reptiles are typically neglected in conservation planning. This is primarily because many species are poorly known, there is limited understanding of population trends, and in many cases detection is difficult, making monitoring unfeasible (Tingley *et al.* 2016; Woinarski 2018). The lack of, or limited, monitoring for most threatened reptiles is a major impediment to conservation recovery (Woinarski 2018; Scheele *et al.* 2019; Gillespie *et al.* 2020). Without adequate monitoring, the impacts of threats are poorly understood, and managers may lose opportunities to prevent extinctions because precipitous declines are not detected with sufficient time to respond (Woinarski 2018).

In 2016, mounting concerns among experts that reptiles were underassessed and under-represented in conservation planning led to a special journal issue of *Biological Conservation*, aiming to address some of the knowledge gaps in reptile conservation (Tingley *et al.* 2016). Following recommendations developed as part of that work, and the IUCN's efforts to complete their Global Reptile Assessment, two workshops were held in 2017 to undertake assessments of the conservation status of all Australian terrestrial squamates (snakes and lizards) against IUCN categories and criteria (Chapple *et al.* 2019; Tingley *et al.* 2019). Here we extend and complement this work by identifying which Australian terrestrial squamates are most likely to go extinct in the next 20 years, an arbitrary period over which change might reasonably be assessed, and which might reasonably be influenced by policy changes made today. We used structured expert elicitation to forecast which, and how many, Australian terrestrial squamates are at imminent risk of extinction, with the aim of improving prioritisation, direction and resourcing of management that could prevent future extinctions. This approach follows estimates of imminent extinction risk among Australian birds, mammals (Geyle *et al.* 2018) and freshwater fish (Lintermans *et al.* 2020). Note that this assessment preceded the 2019–20 wildfires in Australia, which are likely to have severely worsened the conservation outlook for many species.

Materials and methods

Initial selection of species

We considered all Australian terrestrial squamates listed as Critically Endangered (CR), Endangered (EN), or Vulnerable (VU) under Criterion D2 (i.e. restricted area of occupancy or number of locations with a plausible future threat that could drive the species to CR or Extinct in a very short time) (IUCN 2012), based on a recent and comprehensive review using IUCN criteria (Chapple *et al.* 2019; Tingley *et al.* 2019) (a total of 51 species). An additional nine species were added as a consequence of recent revisions of taxonomy and descriptions of new species (Amey *et al.* 2019*a*, 2019*b*; Hoskin *et al.* 2019; Melville *et al.* 2019) to prevent overlooking any species for which a threatened status may be warranted. Note that we do not consider taxonomic revisions or descriptions made after May 2019. In total, 60 of the ~1000 Australian terrestrial squamate species were included in our elicitation. A list of the nine additional species considered, along with justification for their inclusion, is provided as Supplementary Material (see Supplementary Material S1).

Extinct in the wild species

Two Extinct in the Wild (EW) species (Lister's gecko (*Lepidodactylus listeri*) and the blue-tailed skink (*Cryptoblepharus egeriae*)) were also assessed as part of this study. Both species persist in captive colonies, but trial reintroductions into predator-free exclosures on Christmas Island are underway (Andrew *et al.* 2018) and might allow re-establishment of populations within the 20-year timeframe of interest. Following the IUCN definition for successful re-establishment of a wild population, we assume that these species would meet criteria for no longer being EW if (1) reintroductions occur and populations are established within the former range of the species, and (2) individuals persist beyond small fenced exclosures (IUCN 2012). For these two species, we consider the probability that there will be *no wild populations* in 20 years' time, considering this to be the same, conceptually, as the reverse probability of successful re-establishment.

Expert selection

More than 50 key researchers were invited to participate in this study based on their contributions to a recent review of the conservation status of Australia squamates (Chapple *et al.* 2019; Tingley *et al.* 2019). This included individuals from academic institutions, state and federal government offices and agencies, consulting agencies, museums, zoos, and non-government organisations. Just over half (~51%) of those invited agreed to be involved, making up an expert panel of 26 people (all of whom are listed as authors here). All participants had worked with Australian terrestrial squamates and had relevant knowledge of their distributions, ecology and threatening processes.

Structured expert elicitation

We used a structured expert elicitation approach for obtaining estimates of extinction probability (Burgman *et al.* 2011; McBride *et al.* 2012). This approach has been developed in an attempt to reduce the incidence of some commonly encountered biases in expert elicitation processes (McBride *et al.* 2012; Hemming *et al.* 2018). Our adapted elicitation procedure involved four main steps, all of which were conducted remotely via email or phone:

(1) Participants were provided with a summary of the available information on ecology, threats and trends (based largely on the material collated during the recent Red List assessment). This ensured that everyone had the same information available to them when judging a given species' extinction risk. All participants were then asked to estimate the probability of extinction in the wild (or in the case of the two EW Christmas Island species, the probability that there will be no wild populations) in 20 years' time *assuming current levels and direction of management* (Round 1 scores). We also asked participants for an associated level of confidence in their estimates (i.e. very low, low, moderate, high or very high). Participants were able to use additional resources to inform their estimates; however, they were asked not to discuss their scores with any others participating in the expert elicitation (as each individual assessment was to be treated as independent).
(2) Individual estimates of extinction probability and their associated confidence were compiled, and then modelled using a linear mixed-effects model ('lme' in package 'nlme') in R 3.6.0 (R Core Team 2019), where estimates were logit-transformed prior to analysis. We controlled for individual experts consistently underestimating or overestimating likelihood of extinction by specifying their identity as random intercepts. We specified a variance structure in which the variance increased with the level of uncertainty associated with each estimate of likelihood of extinction. Confidence classes of 'very low', 'low', 'moderate', 'high' and 'very high' were converted to uncertainty scores of 90, 70, 50, 30 and 10% respectively.

This model allowed us to predict the probability of extinction (with 95% confidence intervals) for each taxon. Summary statistics (including mean, median, range and outliers) were also calculated, and participants were provided with figures displaying both the summary statistics and their individual estimates so that they could see where their estimates lay relative to the rest of the group (an example is provided in Supplementary Material S2).

(3) Participants were asked to review the results, while noting any concerns about the spread of estimates given for a particular species, outliers or the rankings of extinction probability. Where concerns were raised, participants were invited to provide an anonymous written statement (which was then distributed to the rest of the group). Participants were then encouraged to take part in a teleconference, during which a facilitator drew attention to any marked discrepancies in the draft scores and individual concerns, triggering a general conversation about the interpretation and context of species background information. Each participant was given the opportunity to clarify information about the presented data, introduce further relevant information that may justify either a greater or lesser risk of extinction, and to cross-examine new information. A recording of the teleconference and detailed minutes was provided to all participants, including nine participants who were unable to attend the teleconference.

(4) Participants were then asked to provide a second, final assessment of the probability of extinction (and associated confidence) for each species from which the results were finalised (Round 2 scores).

Estimating the number of species likely to become extinct in the next 20 years

The predicted probabilities of extinction for each of the 60 extant terrestrial squamates (assessed by the experts) were summed to estimate the number of species (from this subset of terrestrial squamates) likely to become extinct in the next 20 years (as per Geyle *et al.* 2018).

Testing for concordance among expert assessments

We measured the level of agreement among experts in the relative ranking of the most imperilled terrestrial squamates using Kendall's Coefficient of Concordance (W) (Kendall and Babinton Smith 1939). This test allows for comparison of multiple outcomes (i.e. assessments made by multiple experts), whilst making no assumptions about the distribution of data. Average ranks were used to correct for the large number of tied values in the dataset, and ranks were compared only for experts who assessed all 60 species ($n = 15$).

Geographic distribution of the most imperilled terrestrial squamates

We mapped the distribution of the most imperilled terrestrial squamates according to their presence in each Interim Biogeographic Regionalisation for Australia (IBRA) subregion (South Australia Department of Environment Water and Natural Resources 2015) using data compiled as part of the recent review (Chapple *et al.* 2019; Tingley *et al.* 2019). Occurrence data were collated from various sources including museums, State and Federal Government Departments, citizen science programs and academic researchers (Tingley *et al.* 2019).

Threatening processes

Threat information was obtained from IUCN (2019) to determine the number and proportion of species threatened by various threat types. We compared these figures with those reported in Tingley *et al.* (2019) to determine if there were any differences in the prevalence of threats affecting the most imperilled terrestrial squamates compared with all IUCN-listed squamates (including those in the Least Concern and Near Threatened categories). Note that this comparison does not consider the relative importance of threats, but rather the total number of species affected by a given threat type. Where threat information was not available (i.e. for the newly described or redefined species listed in Supplementary Material S1), threat information was derived from the published literature and validated by experts. Threat information for *Anilios obtusifrons, Lampropholis bellendenkerensis* and *L. elliotensis* was derived from Chapple *et al.* (2019), who prepared draft assessments for these newly described species, as they lacked IUCN profiles (as of January 2020). Note that threat information was also included for the two EW Christmas Island species.

Results

Expert elicitation, extinction probabilities, and the number of species likely to go extinct

On average, 19 estimates were received for each species (ranging from 16 to 21). Fifteen experts provided estimates for all 60 species, while others chose only to assess species for which they had first-hand experience. Several participants adjusted their Round 1 scores following discussions (including many who did not partake in the teleconference), resulting in changes to the modelled probabilities for every species under consideration (a comparison of Round 1 and 2 modelled outputs is provided in Supplementary Material S3). For most species (~82%), the predicted probability of extinction decreased following discussion, and in some cases by a considerable amount; on average, there was a 4.3% decrease in modelled probability of extinction (ranging from 0.2% for *Saproscincus saltus* to 32.5% for *Tympanocryptis lineata*). The predicted probability of extinction of 11 species (~18%) increased by an average of 8% (ranging from 0.1% for *T. pinguicolla* to 20% for *Saltuarius eximius*) following discussions and re-estimation.

Collation and analysis of expert opinion (Round 2 scores) indicated that six of 60 species are at high risk (likelihood >50%) of becoming extinct within the next 20 years (Table 1, Supplementary Material S4). The six species at highest risk included two agamids (the Victoria and Bathurst grassland earless dragons (*Tympanocryptis pinguicolla* and *T. mccartneyi*)), one blind snake (the Fassifern blind snake (*Anilios insperatus*)) and three skinks (the Lyons grassland striped skink (*Austroblepharus barrylyoni*), the Arnhem Land gorges skink (*Bellatorias obiri*) and the Gravel Downs ctenotus (*Ctenotus serotinus*)). Summing across the extinction risk values assigned by experts to the 60 species assessed, we estimated that 11 species could become extinct in the wild in the next 20 years unless management improves.

Table 1. The probability of extinction (EX) by 2040 (in the wild) for the 20 Australian terrestrial squamates considered to be most imperilled

Likelihoods of extinction are based on structured expert elicitation (with lower/upper 95% confidence intervals) and are ranked from highest to lowest probability of extinction. IUCN refers to the conservation status assigned as part of the recent and comprehensive Red List assessment (Chapple *et al.* 2019; Tingley *et al.* 2019), demonstrating that those species considered to be of greatest extinction risk do not always fall into the highest category of threat, and that those in the Critically Endangered (CR) category are not always considered to be the highest priority. EN, endangered; VU, vulnerable; N/A, unassessed due to recent taxonomic revision or description

Rank	Taxon	EX	Lower 95% CI	Upper 95% CI	IUCN
1	Victoria grassland earless dragon (*Tympanocryptis pinguicolla*)	0.93	0.87	0.96	N/A
2	Fassifern blind snake (*Anilios insperatus*)	0.75	0.60	0.86	CR
3	Lyons grassland striped skink (*Austroblepharus barrylyoni*)	0.71	0.56	0.83	CR
4	Arnhem Land gorges skink (*Bellatorias obiri*)	0.69	0.55	0.80	CR
5	Bathurst grassland earless dragon (*Tympanocryptis mccartneyi*)	0.62	0.45	0.76	N/A
6	Gravel Downs ctenotus (*Ctenotus serotinus*)	0.52	0.33	0.70	CR
7	Allan's lerista (*Lerista allanae*)	0.46	0.31	0.62	CR
8	Christmas Island blind snake (*Ramphotyphlops exocoeti*)	0.41	0.26	0.59	EN
9	Cape Melville leaf-tailed gecko (*Saltuarius eximius*)	0.39	0.24	0.56	EN
10	Mount Surprise slider (*Lerista storri*)	0.37	0.21	0.55	N/A
11	McIlwraith leaf-tailed gecko (*Orraya occultus*)	0.31	0.18	0.48	VU
12	Pinnacles leaf-tailed gecko (*Phyllurus pinnaclensis*)	0.28	0.16	0.44	CR
13	Condamine earless dragon (*Tympanocryptis condaminensis*)	0.25	0.14	0.41	EN
14	Lake Disappointment dragon (*Ctenophorus nguyarna*)	0.21	0.11	0.35	VU
15	Roma earless dragon (*Tympanocryptis wilsoni*)	0.19	0.10	0.32	EN
16	Lake Disappointment ground gecko (*Diplodactylus fulleri*)	0.18	0.09	0.32	VU
17	Canberra grassland earless dragon (*Tympanocryptis lineata*)	0.18	0.10	0.29	N/A
18	Christmas Island forest gecko (*Cyrtodactylus sadleiri*)	0.17	0.10	0.28	EN
19	Lancelin Island ctenotus (*Ctenotus lancelini*)	0.17	0.09	0.29	CR
20	Limbless fine-lined slider (*Lerista ameles*)	0.15	0.07	0.29	EN

There was a reasonable and highly significant degree of conformity among experts (of those who provided estimates for all 60 species, $n = 15$) in their assessments of extinction risk ($W = 0.56$, $P < 0.001$).

Table 2. The probability that there will be no wild populations (EX) by 2040 of the two Extinct in the Wild Christmas Island species considered as part of this study

Both species currently persist as captive breeding colonies and trial reintroductions are underway. Likelihoods are based on structured expert elicitation (with lower/upper 95% confidence intervals) and are ranked from highest to lowest probability

Rank	Taxon	EX	Lower 95% CI	Upper 95% CI
1	Lister's gecko (*Lepidodactylus listeri*)	0.90	0.84	0.94
2	Blue-tailed skink (*Cryptoblepharus egeriae*)	0.89	0.82	0.94

Extinct in the Wild species

A total of 21 experts assessed the probability that there will be no wild populations of Lister's gecko and the blue-tailed skink in 20 years' time, with most experts having little confidence that re-establishment attempts (within their natural range) would be successful. While both species had high probabilities of extinction (suggesting a very low probability of successful re-establishment: Table 2), efforts for the blue-tailed skink were considered slightly less likely to fail by some experts. This was attributed to perceived lower susceptibility to predation compared with Lister's gecko, or due to greater difficulties in establishing populations of Lister's gecko (because of dispersal behaviour and more specialised habitat preferences). Nevertheless, the consensus among experts was that neither species is likely to persist on Christmas Island outside of predator-free exclosures without a significant increase in resources for intense threat management.

Geographic distribution of the most imperilled terrestrial squamates

Three of the terrestrial squamates with highest extinction risk (i.e. those ranking in the top 20: Table 1) occur only on islands: two on Christmas Island, and one on Lancelin Island off the coast of Western Australia (a tiny low-lying sand island <1 km^2 in size). All of the remaining reptiles are endemic to a single state, with more than half (55%) occurring only in Queensland (north-eastern Australia), mostly in the Einasleigh Uplands, Brigalow Belt, Cape York Peninsula and Channel Country biogeographic regions (Fig. 1). The top 20 most imperilled species are restricted in range, with a maximum Area of Occupancy (AOO) of 56 km^2 and an average AOO of $\sim$17 km^2, with most (65%) having an AOO $\leq$16 km^2 (Chapple *et al.* 2019; J. Melville, unpubl. data). The current distribution for one species (the Bathurst grassland earless dragon) is unknown; it has been recorded from only two locations (with records $>$20 years old) (J. Melville, unpubl. data). Several species are known only from a single location (i.e. the Fassifern blind snake, the Lyons grassland striped skink, the Cape Melville leaf-tailed gecko (*Saltuarius eximius*), the Mount Surprise slider (*Lerista storri*), the Pinnacles leaf-tailed gecko (*Phyllurus pinnaclensis*), and the Lake Disappointment dragon (*Ctenophorus nguyarna*) and ground gecko (*Diplodactylus fulleri*): Chapple *et al.* 2019).

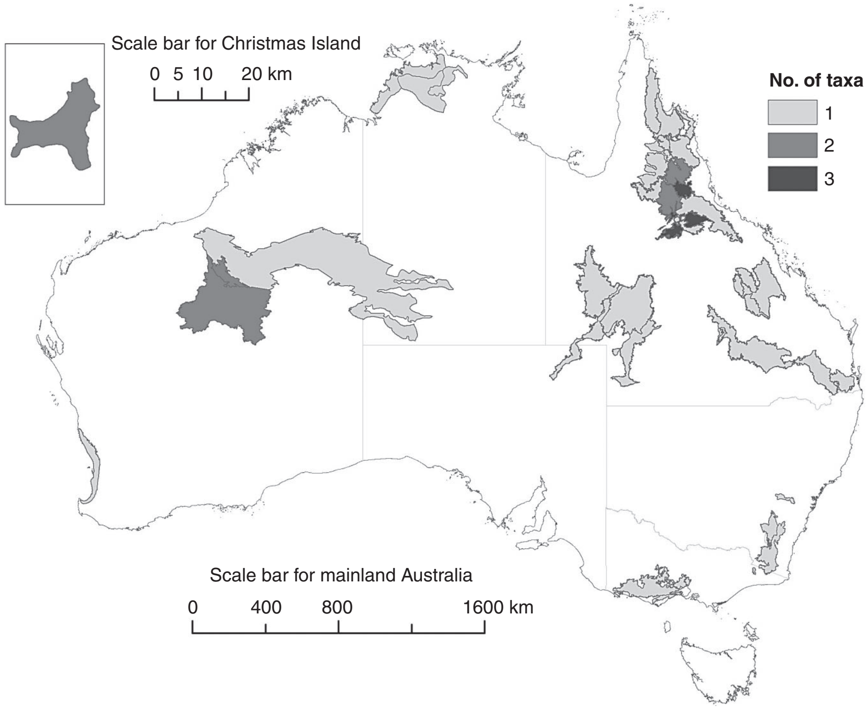

Fig. 1. The number of Australian terrestrial squamates (snakes and lizards) occurring in each Interim Biogeographic Regionalisation for Australia (IBRA) subregion (South Australia Department of Environment, Water and Natural Resources 2015). Data are presented for the top 20 most imperilled terrestrial squamates (based on structured expert elicitation). Occurrence data were collated from various sources including museums, state and federal government departments, citizen science programs and academic researchers (Tingley *et al.* 2019).

Threatening processes

Invasive and other problematic species (i.e. overabundant native species) and diseases were the most prevalent threats to the most imperilled terrestrial squamates, affecting 67.7% ($n = 42$) of the 62 species considered as part of this study (Fig. 2). Within this broader category, weeds (including buffel grass (*Cenchrus ciliaris*), gamba grass (*Andropogon gayanus*) and hawkweed (*Hieracium* spp.), among others) impacted the highest number of species (40%, $n = 25$), followed by the feral cat (*Felis catus*) (29%, $n = 18$) and the red fox (*Vulpes vulpes*) (16%, $n = 10$) (Supplementary Material S5). Approximately 21% of the terrestrial squamate species considered here ($n = 13$) were also impacted directly or indirectly (through habitat degradation or predation) by other invasive species, including black rats (*Rattus rattus*), feral pigs (*Sus scrofa*), deer (*Rusa unicolor* and *Cervus elaphus*), feral horses (*Equus caballus*), invasive invertebrates (*Solenopsis invicta, Anoplolepis gracilipes* and *Scolopendra subspinipes*), Oriental wolf snakes (*Lycodon capucinus*) and cane toads (*Rhinella marina*), while one species was impacted by the native eastern grey kangaroo (*Macropus giganteus*) (through overgrazing of grasslands: Chapple *et al.* 2019). Other notable threats included agriculture (45.2%, $n = 28$), natural system modifications (35.5%, $n = 22$, with 94% of this factor related to inappropriate fire regimes), and climate change and severe weather (30.6%, $n = 19$) (Fig. 2). This ranking of threats was broadly analogous to the threats facing all Australian squamates identified in Tingley *et al.* (2019).

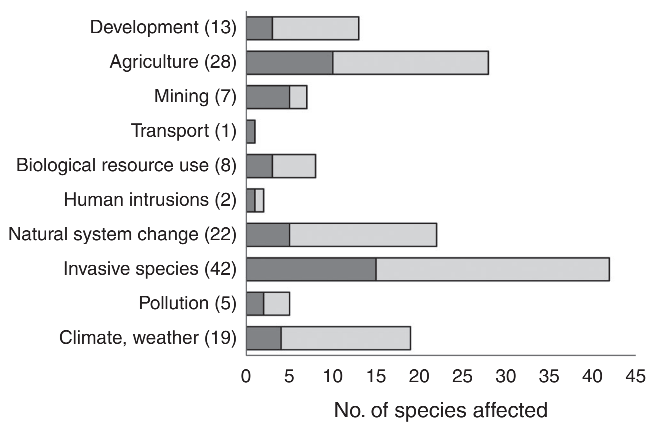

Fig. 2. The number of Australian terrestrial squamates (snakes and lizards) affected by different threat types. Dark grey bars refer to the top 20 most imperilled terrestrial squamates (based on structured expert elicitation), and light grey bars refer to all other species considered as part of this study (including the two EW Christmas Island taxa). The total number of species affected by each threat is shown in parentheses. Note that natural system change includes fire and fire suppression.

Of the top 20 most imperilled species (Table 1), a higher proportion was impacted by invasive species (75%, $n = 15$) and agriculture (50%, $n = 10$) compared with all 62 species considered (including the two EW Christmas Island species), while a smaller proportion were impacted by fire (25%, $n = 5$) and climate change (20%, $n = 4$) (Fig. 2). Notably, of the seven squamate species considered that are affected by energy production and mining, five ranked in the top 20 most imperilled (Fig. 2).

Discussion

The status of Australian terrestrial squamates has deteriorated over the past 25 years, with the proportion of species assessed as threatened nearly doubling since 1993 (Cogger *et al.* 1993; Tingley *et al.* 2019). The last decade has also seen the first documented extinction of an Australian squamate (the Christmas Island forest skink), with two other endemic Christmas Island species becoming extinct in the wild (the blue-tailed skink and Lister's gecko) (Andrew *et al.* 2018; Woinarski 2018). In the wake of continued decline and increasing pressures associated with ongoing threatening processes, it is imperative that extinction risk is recognised in a timely manner to allow for implementation of effective management responses aimed at preventing extinctions (Woinarski *et al.* 2017). Here we used structured expert elicitation to forecast which, and how many, Australian terrestrial squamates are in imminent danger of extinction.

Overall, experts were pessimistic about the state of the species under consideration, with average extinction probabilities estimated to be approximately 20%, and with six species considered to have extinction probabilities greater than 50% in the next 20 years. Additionally, our results suggest that up to 11 species could be lost within this timeframe, a figure that is markedly higher than the already large trajectory of change reported over the previous two decades. While fewer extinctions have been documented for Australian squamates than for other vertebrate groups (i.e. birds, mammals, frogs) (Woinarski *et al.* 2019), the high level of cryptic diversity present in Australian terrestrial squamates, coupled with extensive clearing of key habitat types that may have supported small, narrow-range endemics, and the very restricted ranges of many recently discovered species (Amey *et al.* 2019*a*, 2019*b*; Hoskin *et al.* 2019; Melville *et al.* 2019), suggests that there may have been earlier undetected extinctions. Five of the nine species that we evaluated in addition to the list of species threatened according to IUCN criteria (i.e. those described or revised recently: Supplementary Material S1) ranked in the top 10 most imperilled, further supporting this observation.

There is greater uncertainty associated with the conservation status of squamates in Australia relative to other terrestrial vertebrate groups, primarily due to high levels of data deficiency. For example, 61 of the 1020 squamate species (~6%) considered in the Australian review were categorised as Data Deficient (Chapple *et al.* 2019), a far higher rate than for comparable reviews of Australian birds (none) (Garnett *et al.* 2011) and terrestrial mammals (~0.9%) (Woinarski *et al.* 2014). It is also possible that the two species ranked with highest extinction risk here are already extinct. The Victoria grassland earless dragon has not been seen for several decades despite extensive survey effort (Robertson and Evans 2009; Banks *et al.* 2017); however, as some potential habitat in its range in western Victoria remains unsurveyed, it is possible that one or more small populations persist in remnant grasslands (Banks *et al.* 2017; Melville *et al.* 2019). The Fassifern blind snake is known only from the holotype (collected in 1992), despite several attempts to locate additional specimens (Venchi *et al.* 2015). If not extinct, then this species is likely to be of extreme conservation concern, as the type locality is close to the large and expanding urban areas of Brisbane and Ipswich, and the single site from which it is known has been extensively cleared (Venchi *et al.* 2015). Further surveys are required to determine whether either of these species are extant (Venchi *et al.* 2015; Melville *et al.* 2019).

A notable feature of our results is the generally higher risk of extinction predicted for the most-at-risk terrestrial squamates relative to a previous study conducted on Australian mammals using the same methods, but the comparatively similar results for Australian birds (Geyle *et al.* 2018). This pattern may be because many of the squamates considered in this study are persisting in remnant pockets of vegetation adjacent to highly developed areas (e.g. the Bathurst grassland earless dragon and Allan's lerista (*Lerista allanae*)), similarly to the most imperilled birds, and consequently also face a high risk of extinction due to habitat loss, fragmentation, and edge effects (Haddad *et al.* 2015). By contrast, many mammals have already been lost from these areas, with future extinctions predicted to occur in the less developed parts of central and northern Australia (Geyle *et al.* 2018). Another contributing factor may be that many squamates occupy extremely restricted ranges (~68% of the species assessed have an estimated Area of Occupancy <100 km^2), making them particularly vulnerable to stochastic events (Murray *et al.* 2017). Furthermore, squamates generally lack the public and political appeal that helps catalyse recovery support for other Australian threatened vertebrates, leading to relatively little resourcing for conservation (Woinarski 2018). By contrast, there are generally more well-established and coordinated management efforts for mammals and birds, with many mammal species that were previously highly imperilled showing substantial recent recovery as result of predator exclusion and translocation (Kanowski *et al.* 2018; Moseby *et al.* 2018; Read *et al.* 2018).

Our analysis of threats facing the most imperilled terrestrial squamates was consistent with that reported for all terrestrial squamate species in Tingley *et al.* (2019), and with other studies that have identified invasive species, habitat loss or modification (i.e. through agriculture, urbanisation, altered fire regimes and mining) and climate change as major threats (Sinervo *et al.* 2010; Böhm *et al.* 2016*b*). A substantial suite of threatened reptiles are closely associated with habitats that are currently being cleared at a high rate (notably temperate grasslands of south-eastern Australia and brigalow woodlands of central Queensland), providing indirect evidence of substantial declines for those species (Woinarski 2018). For several other species persisting in already highly modified landscapes, changing land-use is likely to contribute further to declines. For example, a shift from mixed-crop farms to broadacre monocultures (often irrigated cotton) in the Condamine River floodplains has led to the destruction of critical habitat for the Condamine earless dragon (*Tympanocryptis condaminensis*) (Melville 2018).

This suggests that an increase in the projected number of extinctions over the next two decades is plausible. An important lesson may be learnt from Christmas Island: despite evidence of decline in at least four of the island's six native squamates from the 1970s to the 1990s (Cogger and Sadlier 1999), relatively few resources were invested for management and monitoring. Consequently, the rate and scale of decline (and its cause) was not appreciated in time to prevent extinctions (Woinarski *et al.* 2017), in an alarming parallel to the recent extinction of the Christmas Island pipistrelle (*Pipistrellus murrayi*) (Martin *et al.* 2012).

The probability of further extinctions of Australian squamate species is high, particularly in the face of increasing pressures associated with climate change, which are not yet well understood, and may have been underestimated here. Notably, at least 17 squamate species (including five considered as part of this study) have been substantially affected by the widespread and catastrophic wildfires that devastated eastern and southern Australia in late 2019 and early 2020 (Department of Environment and Energy 2020; Department of Environment, Land, Water and Planning 2020). Our assessment was undertaken before these fires, and it is possible that they may have added to the list of species that should have been considered. It is still too early to determine the impact (both short- and long-term) of the fires at a species level. Nevertheless, and notwithstanding potential fire impacts, our results suggest that up to 11 species could become extinct by 2040 under current management regimes. A more strategic, better-resourced conservation response is urgently required if we are to avert future extinctions of Australia's terrestrial squamates.

Conflicts of interest

The authors declare no conflicts of interest.

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