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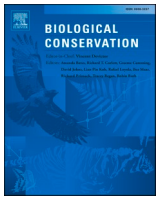

Conservation status of the world's skinks (Scincidae): Taxonomic and geographic patterns in extinction risk

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ABSTRACT

Our knowledge of the conservation status of reptiles, the most diverse class of terrestrial vertebrates, has improved dramatically over the past decade, but still lags behind that of the other tetrapod groups. Here, we conduct the first comprehensive evaluation (~92% of the world's ~1714 described species) of the conservation

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Lizard
Protected areas
Reptile
Skink
Taxonomic bias

status of skinks (Scincidae), a speciose reptile family with a worldwide distribution. Using International Union for Conservation of Nature (IUCN) criteria, we report that ~20% of species are threatened with extinction, and nine species are Extinct or Extinct in the Wild. The highest levels of threat are evident in Madagascar and the Neotropics, and in the subfamilies Mabuyinae, Eugongylinae and Scincinae. The vast majority of threatened skink species were listed based primarily on their small geographic ranges (Criterion B, 83%; Criterion D2, 13%). Although the population trend of 42% of species was stable, 14% have declining populations. The key threats to skinks are habitat loss due to agriculture, invasive species, and biological resource use (e.g., hunting, timber harvesting). The distributions of 61% of species do not overlap with protected areas. Despite our improved knowledge of the conservation status of the world's skinks, 8% of species remain to be assessed, and 14% are listed as Data Deficient. The conservation status of almost a quarter of the world's skink species thus remains unknown. We use our updated knowledge of the conservation status of the group to develop and outline the priorities for the conservation assessment and management of the world's skink species.

1. Introduction

"*Knowledge is Power*"

(*Francis Bacon, 1597*)

This adage is no better exemplified than in the field of conservation biology, as we cannot effectively conserve species that we do not know are threatened, and we cannot ensure the long-term persistence of threatened species unless we understand the threats that they face. This knowledge is the foundation of effective conservation policy and management (Soulé, 1985; Primack, 2014). Since 1964, the International Union for Conservation of Nature (IUCN) Red List of Threatened Species has been the primary source of this knowledge for conservation biologists internationally. Understanding the conservation status (and threats) of every known species is a key goal for conservation biologists as it would enable informed conservation planning and actions. However, there are few instances where information has been complete and subsequent management plans have been able to be effectively implemented (IUCN, 2020). Whilst terrestrial vertebrates are the world's most studied group, ~25% of species remain to be assessed against IUCN Red List criteria (IUCN, 2020). Despite considerable advancement over the past few years due to the progress made in achieving the IUCN's first Global Reptile Assessment (Böhm et al., 2013; Meiri and Chapple, 2016; Tolley et al., 2016, 2019; Tingley et al., 2016, 2019; Chapple et al., 2019), reptiles remain the most under-assessed terrestrial vertebrate group, with ~30% of the world's ~11,350 species unassessed by the end of 2020 (IUCN, 2020; and probably ~10% during 2021).

Here we provide the first detailed overview of the conservation assessment of skinks (Scincidae), a diverse (~1714 described species; Uetz et al., 2020) family of terrestrial vertebrates. Skinks represent a quarter of lizard diversity worldwide (Uetz et al., 2020). They have a near-global distribution, with species richness hotspots in Australia, New Guinea, south-east Asia, sub-Saharan Africa, and Madagascar (Fig. 1). The species richness of skinks is mirrored by their extreme morphological, ecological, and life-history diversification (Greer, 2007). For instance, skinks exhibit a 17-fold variation in adult body length and an 1800-fold difference in adult body mass (Greer, 2007; Meiri, 2018). There have been multiple cases of evolution from limbed to limb reduction and/or loss (25+ transitions; Greer, 1991), four independent origins of the enigmatic evolution of green blood (Rodriguez et al., 2018), and 31+ evolutionary shifts from oviparity to viviparity (Blackburn, 1982, 1999, 2015). Furthermore, all six of the amniote clades that have converged on the "mammalian" pattern of complex placentation and placentotrophy (except mammals) are skinks (Blackburn, 2015; Griffith and Wagner, 2017). Skinks also display considerable variation in ecological and life history traits, such as activity times, foraging mode, thermal preferences, microhabitat use, clutch (litter) size and frequency, sociality, and diet, with several species exhibiting long-term stable social aggregations (Chapple, 2003; Gardner et al., 2016; While et al., 2019) and herbivory (Chapple, 2003), which are rare in squamates in general. Worryingly, skinks, whilst comprising 24% of recognised lizard species comprise ~45% of documented, presumably

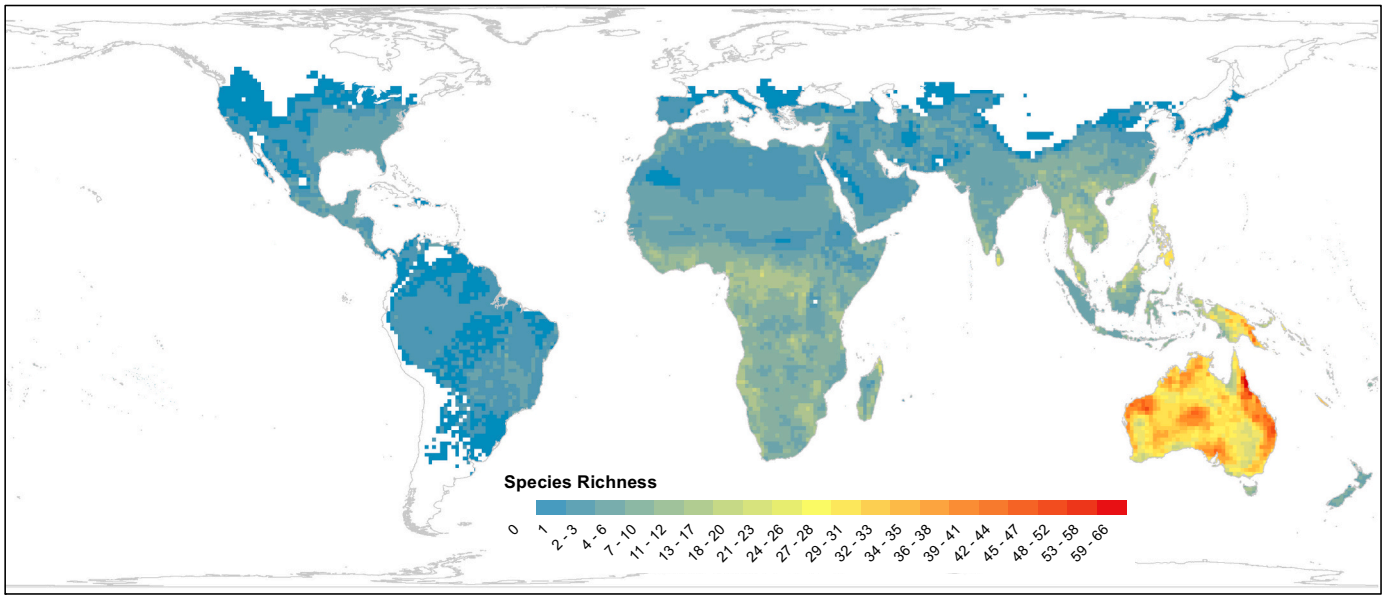

Fig. 1. Global species richness of skinks (Scincidae).
Data from Global Assessment of Reptile Distributions (GARD; http://www.gardinitiative.org/), 2019.

human-mediated, lizard extinctions (20 of 45 species) that have occurred in the late Quaternary (Slavenko et al., 2016).

Global reptile populations are thought to have declined by ~55% over the past 50 years (Saha et al., 2018). However, several factors have inhibited our ability to gauge the current conservation status of skinks. First, we are yet to fully grasp the true species richness of skinks. Skinks continue to be described at a substantial rate (~20 species per year during the last decade, Fig. 2; Uetz et al., 2020). Skink numbers accumulate not only via the discovery and description of new species, but also through the splitting of species complexes. This means that not only do the species newly described and newly elevated from synonymy need to be assessed, but the recognised species impacted by the revision of species complexes, and the subsequent reduced geographic range of some species, need to be re-assessed (i.e. at least a 2-fold increase in the required number of conservation assessments). Second, we have limited knowledge of the distribution, biology, and ecology of most skink species (Roll et al., 2017; Meiri, 2018; Meiri et al., 2018). This is a result of the sheer number of species to study, the fact that the major centres of skink diversity (i.e. central Australia, New Guinea, south-east Asia, central Africa; Fig. 1) are located in remote, inaccessible locations, and/or in regions well away from areas where there are high concentrations of herpetologists (Greer, 2007; Tingley et al., 2019; Chapple et al., 2019), and limited funding for studies of basic ecology and biology (e.g. Crowther et al., 2012; Lindenmayer et al., 2012). This has limited our knowledge of skink species biology and threatening processes, which has in turn led to skinks (and squamates more broadly) having a high proportion of Data Deficient and non-assessed species (Böhm et al., 2013; Tingley et al., 2016; Meiri and Chapple, 2016; Bland and Böhm, 2016). Finally, there is relatively little information on the long-term population trends of skinks (Saha et al., 2018; Woinarski, 2018). This has led to the Red List accounts of skinks (and squamates in general) being less detailed than those of most other terrestrial vertebrate groups (e.g., birds, turtles) (Böhm et al., 2013; Tingley et al., 2016, 2019).

As a step towards rectifying these knowledge gaps, the IUCN SSC Skink Specialist Group (SSG) was established in July 2018 (https://www.skinks.org/). The SSG currently has ~160 members, composed of a global network of biologists and wildlife managers that are actively involved in research and conservation-related activities on the world's skinks. The core goals of the SSG are to (1) complete Red List assessments for all described skink species to identify threatened species, and (2) co-ordinate conservation management for threatened skink species worldwide. To achieve these goals, we conducted the first comprehensive overview of the conservation assessment of skinks worldwide. Specifically, we reviewed the current conservation status of skinks, in terms of the number of species that have been assessed, the proportion of assessed species that are threatened, and the number that remain to be assessed. To develop conservation priorities for skinks, we investigated geographic and taxonomic patterns in extinction risk and threats. Finally, we examined the degree to which threatened, Data Deficient, and Not Evaluated species overlap with protected areas. This information can be used to develop conservation plans and priorities for skinks, including a strategy to complete assessments for all described skink species globally.

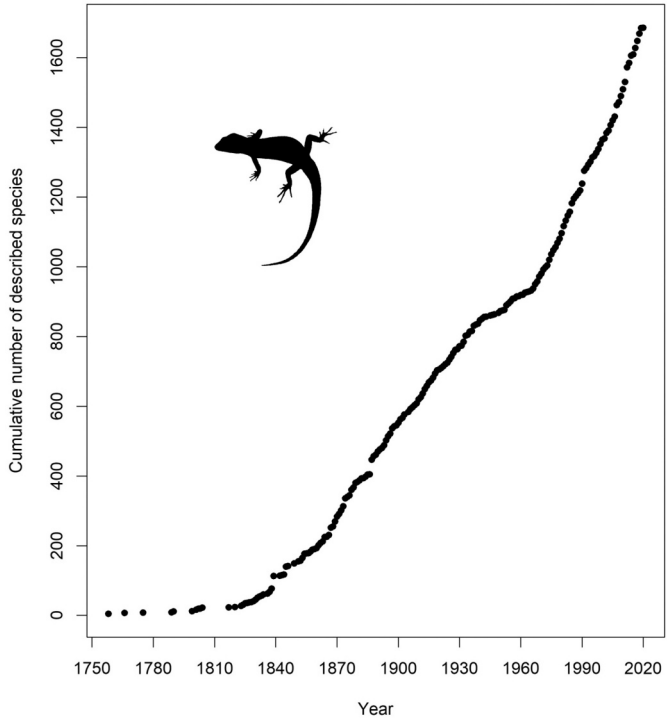

Fig. 2. Growth in currently recognised skink (Scincidae) species over time.

2. Materials and methods

2.1. Conservation status and distribution of skinks

We used the data from all skink species that were assessed as part of the Global Reptile Assessment, which was finalised in mid-2020. After updating the list for current taxonomy (Uetz et al., 2020, and additional amendments), we used Red List assessments for 1578 skink species globally (Table 1). As at July 2020, the IUCN SSC Skink Specialist Group recognised 1714 described skink species globally. Thus, 136 species were Not Evaluated against IUCN Red List criteria (Table 1). Distributional data for all 1714 described skink species were obtained from version 1.7 of the Global Assessments of Reptile Distributions (GARD; http://www.gardinitiative.org/), which is an updated version of the datasets published in Roll et al. (2017) and Gumbs et al. (2020). The distributional patterns identified using either point locality or polygon data were concordant (Fig. S1), therefore our distributional maps and analyses are based on the polygon data from GARD. Data on the year of description for each skink species were obtained from Uetz et al. (2020). Seven monophyletic skink subfamilies are currently recognised (Acontinae, Egerniinae, Eugongylinae, Lygosominae, Mabuyinae, Scincinae, Sphenomorphinae; Hedges, 2014; Uetz et al., 2020). We examined differences in the conservation status and extinction risk among these clades.

2.2. Estimating overall extinction risk

Species classified as Data Deficient (DD), and those that are Not Evaluated (NE), introduce uncertainty into calculations of the percentage of threatened species (i.e. those classified as Vulnerable, Endangered, or Critically Endangered out of all species). We therefore estimated the percentage of threatened species using three different approaches to the treatment of Data Deficient species (Böhm et al., 2013; Tingley et al., 2019).

Our first approach involved assuming that the true extinction risk of Data Deficient and Not Evaluated species would fall into the three threatened categories in the same proportions as observed in currently assessed species: $(CR + EN + VU)/(N - EX - EW - DD)$, where N is the total number of evaluated skink species worldwide, EX and EW refer to the number of Extinct and Extinct in the Wild species, respectively, and CR, EN, VU, and DD are, respectively, the numbers of Critically Endangered, Endangered, Vulnerable, and Data Deficient species. Second, we produced an optimistic (lower bound) estimate of the percentage of threatened species by assuming that no Data Deficient and Not Evaluated species were threatened: $(CR + EN + VU)/(N + NE - EX - EW)$. Finally, we produced a pessimistic estimate by assuming that all Data Deficient and all Not Evaluated species were threatened: $(CR + EN + VU + DD + NE)/(N + NE - EX - EW)$. Extinct and Extinct in the Wild species were excluded from spatial analyses. We calculated the Red List

Table 1
Number of skink (Scincidae) species in each IUCN Red List category within each biogeographic realm and subfamily. EX = Extinct, EW = Extinct in the Wild, CR = Critically Endangered, EN = Endangered, VU = Vulnerable, NT = Near Threatened, LC = Least Concern, DD = Data Deficient, NE = Not Evaluated. The calculations for percentage threatened area: current knowledge (CR + EN + VU)/(N − EX − EW − DD); optimistic (CR + EN + VU)/(N + NE − EX − EW); pessimistic (CR + EN + VU + DD + NE)/(N + NE − EX − EW). Red List Index: 1 refers to all species being Least Concern and 0 referring to all species being Extinct (as per Butchart et al., 2007).

	EX/EW	Threatened			NT	LC	Non-classifiable		Total	Red List Index	% Threatened		
		CR	EN	VU			DD	NE			Current knowledge	Optimistic	Pessimistic
Realm													
Afrotropic	2/0	5	9	8	12	165	36	8	245	0.91	11.1%	9.1%	23.9%
Australasia	1/0	28	59	48	24	549	60	31	800	0.9	19.1%	16.9%	24.4%
Indomalay	1/1	5	18	12	26	157	92	72	382	0.88	16.2%	9.2%	33.4%
Madagascar	2/0	6	8	15	8	33	17	7	94	0.74	42.6%	31.5%	50.0%
Nearctic	0	1	0	1	0	15	2	5	24	0.93	11.8%	8.3%	16.7%
Neotropic	2/0	26	4	3	1	36	7	8	87	0.63	47.1%	38.8%	47.1%
Palaearctic	0	2	3	3	5	53	7	5	78	0.92	12.1%	10.3%	19.2%
Subfamily													
Acontinae	0	0	0	0	1	27	3	0	31	0.99	0%	0%	1.3%
Egerniinae	0	1	4	2	3	44	4	4	62	0.91	13.0%	11.3%	24.2%
Eugongylinae	4/1	23	47	44	14	252	43	19	447	0.81	30.0%	25.8%	39.8%
Lygosominae	0	0	0	0	0	32	17	5	54	1.00	0%	0%	40.7%
Mabuyinae	3/0	27	10	11	8	121	22	20	222	0.79	27.1%	21.9%	41.1%
Scincinae	1/0	13	21	19	23	137	39	40	293	0.83	24.9%	18.2%	45.2%
Sphenomorphinae	0	9	19	14	27	395	93	48	605	0.93	9.1%	6.9%	30.2%
Overall	8/1	73	101	90	76	1008	221	136	1714	0.87	19.6%	15.5%	36.4%

Index (RLI, as per Butchart et al., 2007) for each region and subfamily. The RLI value was calculated by multiplying the number of species in each red list category by the category weight (0 for Least Concern [LC], 1 for Near Threatened [NT], 2 for VU, 3 for EN, 4 for CR and 5 for EX). The product of these was summed and then divided by the maximum possible product (number of species multiplied by the maximum weight of 5). This value was then subtracted from one to produce the RLI score for the group. This produces an index value that ranges from 0 to 1, where 1 refers to all species being Least Concern and 0 refers to all species being Extinct. Population trajectories for each species were categorised according to the IUCN Red List assessments (as stable, increasing, decreasing, or unknown/not evaluated), for each skink species.

2.3. Geographic and taxonomic patterns of extinction risk

Species geographic range maps from GARD were overlaid on a 96.486 km × 96.486 km grid in a global Behrmann equal area projection (roughly 1 * 1° at the equator), to estimate spatial patterns of species richness. Our initial analyses indicated that grid size resolution did not affect species richness estimates, as previously reported by Roll et al. (2017). Maps were produced for (i) all skink species (N + NE); (ii) threatened species (CR + EN + VU); (iii) Data Deficient (DD) species; (iv) Not Evaluated (NE) species; and (v) unclassifiable (DD + NE) species. We tallied the absolute numbers of species in these categories within each grid cell. We also evaluated whether threatened species were randomly distributed among subfamilies and biogeographic realms (according to the realm definition of the World Wildlife Fund: https://www.worldwildlife.org/biomes) using chi-square tests of independence. In addition, we examined the distribution of EDGE (Evolutionary Distinct and Globally Endangered; https://www.edgeofexistence.org/) skink species, using both the mean, and sum, EDGE score for each grid square.

2.4. Threatening processes

Major threats were identified for each skink species in the IUCN Red List assessments. We used these data to map the number of species threatened by the types of threat listed for the largest number of skink species: agriculture, invasive species, biological resource use (e.g., hunting and collecting of animals; logging and wood harvesting), residential and commercial development (e.g., housing and urban developments, commercial and industrial areas, tourism and recreational activities), natural systems modifications (e.g., fire and fire suppression, dams and water management/use), energy production and mining, and climate change and severe weather. We did this for all species irrespective of their IUCN status (some non-threatened species are listed as being subjected to such threats, but this is not done for all species).

2.5. Protected area coverage

We calculated the proportion of each species' geographic range that fell within the global protected area network, using range data from GARD and protected area data from the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC, 2020) and IUCN (2020) (https://www.iucn.org/theme/protected-areas/about/protected-area-categories). We considered two types of protected areas in our analysis: (i) strict nature reserves (IUCN Category Ia Strict Nature Reserve, and Ib Wilderness Area), and (ii) reserves set aside for nature (IUCN Categories I–IV; II National Park, III Natural Monument or Feature, IV Habitat/Species Management Area). We examined geographic range overlap with both types of protected areas separately for (i) Data Deficient, (ii) threatened (VU, EN, CR), (iii) non-threatened (LC, NT), and (iv) Not Evaluated species.

3. Results

3.1. Overall extinction risk

Of the 1578 skink species that have been assessed against IUCN Red List criteria, 1008 (63.9%) were assessed as Least Concern (Table 1). Seventy-six species (4.8%) were classified as Near Threatened, and 264 species (16.7%) were listed as threatened. Within the threatened categories, 73 (4.6%) were evaluated as Critically Endangered, 101 (6.4%) as Endangered, and 90 (5.7%) as Vulnerable (Table 1). In addition, eight species are listed as Extinct (*Alinea luciae*, *Chioninia coctei*, *Copeoglossum redondae*, *Emoia nativitatis*, *Leiolopisma ceciliae*, *Leiolopisma mauritianum*, *Scelotes guentheri*, *Tachygyia microlepis*) and one as Extinct in the Wild (*Cryptoblepharus egeriae*) (Table 1). Eight of the nine species classified as Extinct or Extinct in the Wild (all except *Scelotes guentheri*) were endemic to islands and some of them showed remarkable island gigantism (e.g., *C. coctei* from Cabo Verde and *L. mauritianum* from Mauritius). A substantial number of species (221 species; 14.0%) were classified as Data

Deficient (Table 1). When combined with the 136 skink species (7.9% of described species; as of July 2020) that are yet to be evaluated against IUCN Red List criteria, 357 species (20.8% of described skink species) are unclassified (Table 1). The estimated total percentage of threatened (i.e. Vulnerable, Endangered or Critically Endangered) skink species is 19.6%, with an optimistic estimate of 15.5% (i.e., all DD and NE species are not threatened) and a pessimistic estimate (i.e., including all DD and NE species) of 36.4% (Table 1). The overall Red List Index for skinks is 0.87 (Table 1). Population trends were assessed as stable for 41.8% (n = 657) of species, decreasing for 14.2% (n = 223), increasing for 0.5% (n = 8), and unknown for 43.4% (n = 681) (Table 2).

The vast majority of threatened species (220 of 264 species; 83.3%; Table 3) were classified based largely on having a restricted geographic range (Extent of Occurrence less than 20,000 km^2), typically with an ongoing threat that further reduces this distribution, or the quality of habitat within it (IUCN Criterion B). Only ten species were classified under Criterion A (severe [>30%] reductions in population size over the last ten years or three generations), and five under Criterion C (small population size and population decline; *Bellatorias obiri*, *Liopholis kintorei*, *Oligosoma albornense*, *O. hoparatea*, and *Phoboscincus bocourti*). Thirty-nine of the threatened species (14.8%) were listed under Criterion D (generally D2 [87.2%]: small area of occupancy or few locations, with a highly plausible near-future threat) (Table 3); thus, over 90% of threatened skink species are evaluated chiefly on the basis of their small ranges. No skink species (and indeed, only two reptile species) have been listed under Criterion E (quantitative analysis of extinction risk) (Table 3), again reflecting the overall poor knowledge of their status. Extinct and Extinct in the Wild skink species were generally described earlier than species in other Red List categories (Table 4). In contrast, Least Concern species have earlier description dates than either threatened species or Data Deficient species (Table 4), implying that species not yet described may well be threatened. Not Evaluated species have generally been described in the last 2–3 decades (Table 4).

3.2. Geographic and taxonomic patterns of extinction risk

Skink species richness is highest in Australia, New Guinea, south-east Asia, Pacific Islands, Madagascar, and continental Africa (Fig. 1). Whilst the geographic patterns of threat (% threat, Red List Index) were often congruent with these diversity hotspots (i.e. New Caledonia 65% of species threatened; Madagascar, Neotropics >40% of species threatened), other areas of species richness had lower percentages of threat (10–20%; Afrotropics, Australasia, Indomalayan, Nearctic, Palaearctic; about 11, 19, 16, 12 and 12% of species threatened, respectively, χ^2 = 69.0, $p < 0.0001$), threat levels (Table 1; Fig. 3). The mean EDGE score was highest in Asia, India, the Middle East, northern Africa, and Madagascar (Fig. S2a). In contrast, the sum of EDGE scores was greatest in Australia, New Guinea, Asia, southern Africa, and Madagascar (Fig. S2b). Skink species richness was associated with the sum of EDGE scores (Fig. S2d), but not the mean EDGE score (Fig. S2c).

There was clear evidence for a taxonomic signal in threat, with a higher proportion of threatened species relative to the number of assessed species in Mabuyinae (~27% threatened), Scincinae (~25%), and Eugongylinae (~30%), a lower proportion of threatened species in Egerniinae (~13%) and Sphenomorphinae (~9%) and no threatened species in the Acontinae and Lygosominae (Table 1; χ^2 = 85.1, p < 0.0001). Similarly, the Red List Index was lowest (i.e. higher extinction risk) in the Mabuyinae, Eugongylinae and Scincinae, and highest (i.e. lower extinction risk) in Acontinae and Lygosominae (Table 1).

Non-classifiable skinks, both Data Deficient and Not Evaluated species, were more commonly distributed in Australia, Africa, New Guinea, southern India, and south-east Asia (Fig. 4). Similarly, the proportion of DD and NE species was highest in the Indomalayan (42.9%), Nearctic (29.2%), and Madagascar (25.5%) regions (χ^2 = 542.6, p < 0.0001; Table 1). Non-classifiable species were a common feature of all skink subfamilies (9.7–40.7% of species), but highest in Lygosominae (40.7%), Scincinae (26.9%), and Sphenomorphinae (23.3%) (χ^2 = 41.9, p < 0.0001; Table 1).

3.3. Threatening processes

Agriculture (including land clearing for crops, plantations, and livestock) is the most prevalent threat to skinks worldwide (25.1% of species, n = 396), followed by invasive and other problematic species and diseases (16.7%, n = 263) and biological resource use (15.0%, n = 236). The other relevant threats to skinks include residential and commercial development (10.8%, n = 170), natural systems modifications (9.4%, n = 148), energy production and mining (6.8%, n = 107), and climate change and severe weather events (4.0%, n = 63).

Effects of agriculture were most common in Madagascar, Australia, New Caledonia, New Zealand, and south-east Asia (Fig. 5a). The impacts of invasive species and natural systems modifications were most pronounced in Australasia (Australia, New Caledonia, New Zealand; Fig. 5b, e), whereas biological resource use was most widespread in Madagascar and south and south-east Asia (Fig. 5c). Effects of residential and commercial development were most prevalent in Australia (especially the south-east and south-west regions), the Indo-Malay, and northern Africa (Fig. 5d). The impacts of mining and energy production were most pronounced in Australasia (Australia, New Caledonia, New Zealand) and Madagascar (Fig. 5f).

Table 2
Population trends for skink (Scincidae) species that have been assigned an IUCN Red List category. CR = Critically Endangered, EN = Endangered, VU = Vulnerable, NT = Near Threatened, LC = Least Concern, DD = Data Deficient. Extinct, and Extinct in the Wild, species have been excluded. Percentages are out of the number of species in each threat category.

Category	Decreasing	Increasing	Stable	Unknown	Overall
CR	44 (60.3%)	0	3 (4.1%)	26 (35.6%)	73
EN	68 (67.3%)	0	4 (4.0%)	29 (28.7%)	101
VU	42 (46.7%)	5 (5.6%)	8 (8.9%)	35 (38.9%)	90
NT	32 (42.1%)	1 (1.3%)	17 (22.4%)	26 (34.2%)	76
LC	36 (3.6%)	2 (0.2%)	616 (60.1%)	354 (35.1%)	1008
DD	1 (0.5%)	0	9 (4.1%)	211 (95.5%)	221
Overall	223 (14.2%)	8 (0.5%)	657 (41.8%)	681 (43.4%)	1569

Table 3
Number of threatened skink (Scincidae) species (n = 264) that are listed under each IUCN Red List criterion. Note that several species are listed under multiple criteria (and hence percentages sum to >1).

Criterion	Number of species
A	10 (3.8%)
B	220 (83.3%)
C	5 (1.9%)
D	39 (14.8%)
E	0

Table 4
Mean date of description (±SE) for skink (Scincidae) species assigned to each IUCN Red List category.

IUCN Red List category	Mean year described
Extinct (EX)/Extinct in the Wild (EW)	1902 ± 21.3
Critically Endangered (CR)	1966 ± 7.3
Endangered (EN)	1951 ± 5.4
Vulnerable (VU)	1956 ± 5.6
Near Threatened (NT)	1946 ± 6.6
Least Concern (LC)	1921 ± 1.9
Data Deficient (DD)	1953 ± 3.3
Not Evaluated (NE)	1999 ± 3.0

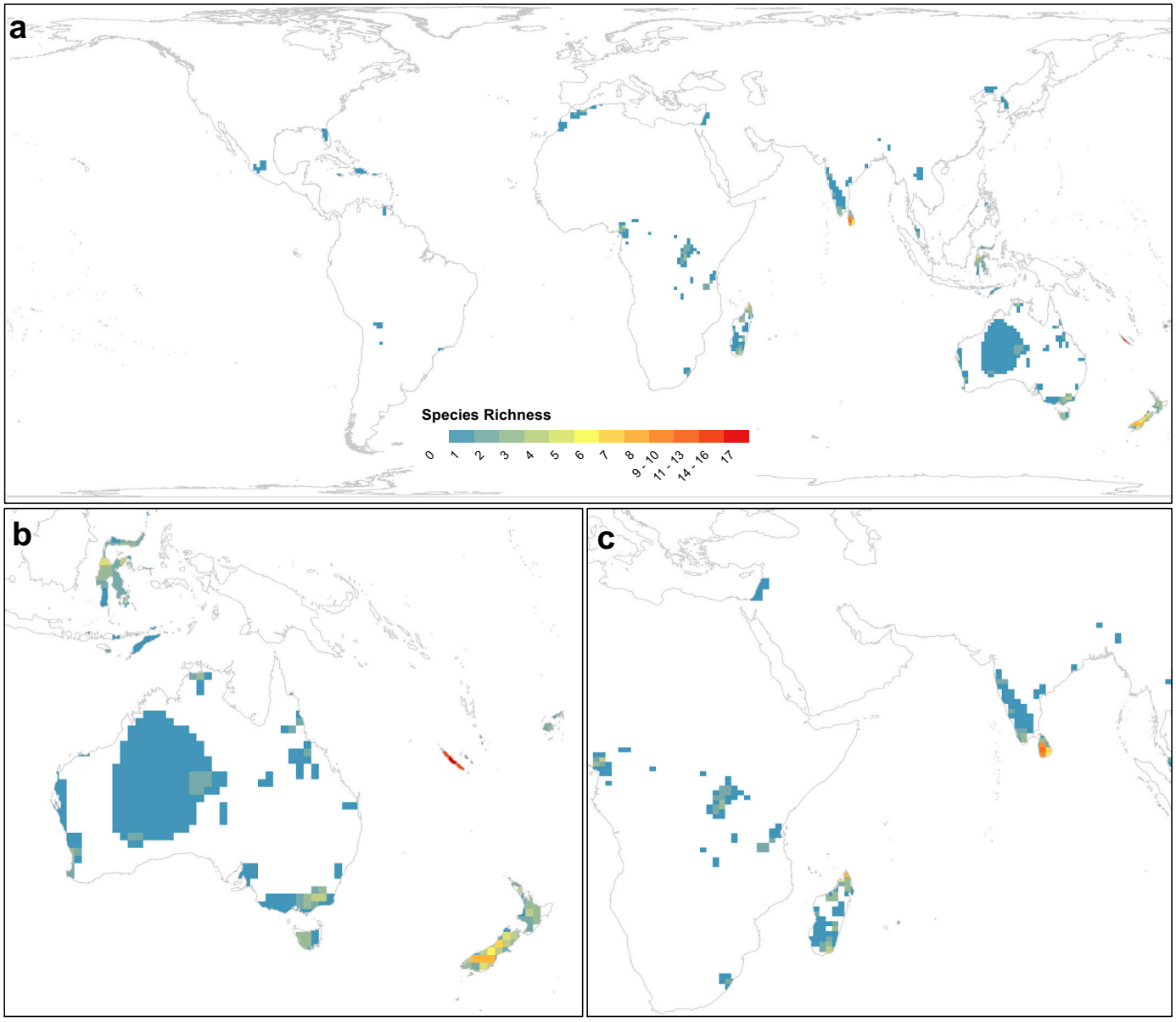

Fig. 3. Species richness of threatened skinks (Scincidae) (A) globally, and in richness hotspots in (B) Australia and New Zealand (note New Caledonia), and (C) Madagascar and South Asia (Sri Lanka and Peninsular India).
Data from Global Assessment of Reptile Distributions (GARD; http://www.gardinitiative.org/), 2019.

3.4. Protected area coverage

The results of our analyses revealed that distributions of skink species had little overlap with protected areas. The proportion of each species' geographic range that overlapped the global protected area network did not vary substantially among species listed under the different IUCN Red List categories, regardless of whether we examined strict nature reserves (IUCN Category I; Fig. S3A), or all reserves set aside for nature (IUCN Categories I–IV; Fig. S3B). In fact, 80% of species did not occur in a single strict nature reserve, and 61% of species did not occur in a single reserve set aside for nature. The number of species that did not overlap any protected area was similarly quite consistent among species listed under the different IUCN Red List categories (Table 5), although non-evaluated species tended to be the most poorly represented group.

4. Discussion

We conducted the first comprehensive analysis (~92% of the world's 1714 described species) of the conservation status of skinks, finding that one in five species are threatened with extinction, and nine species are Extinct or Extinct in the Wild. Taxonomic and geographic patterns are clearly evident, with higher levels of threat in New Caledonia and Madagascar (including the Mascarene Islands); for the latter it is where many skinks are microendemic, fossorial, and specialize on threatened habitats such as dry forest with sandy soil, or primary rainforest. Threat levels were also high in the Neotropics, although this region is generally skink-poor. Extinction risk was also higher in the subfamilies Mabuyinae, Eugongylinae, and Scincinae (Table 1). The vast majority of threatened skink species (96%) were listed based primarily on a restricted geographic range and a current, or inferred, threat (Criteria B, and D2). Although the population trend of ~42% of the species is stable, information on temporal trends in population size (or a suitable proxy) of ~43% of species is unknown (Table 2). Around 14% of skink species

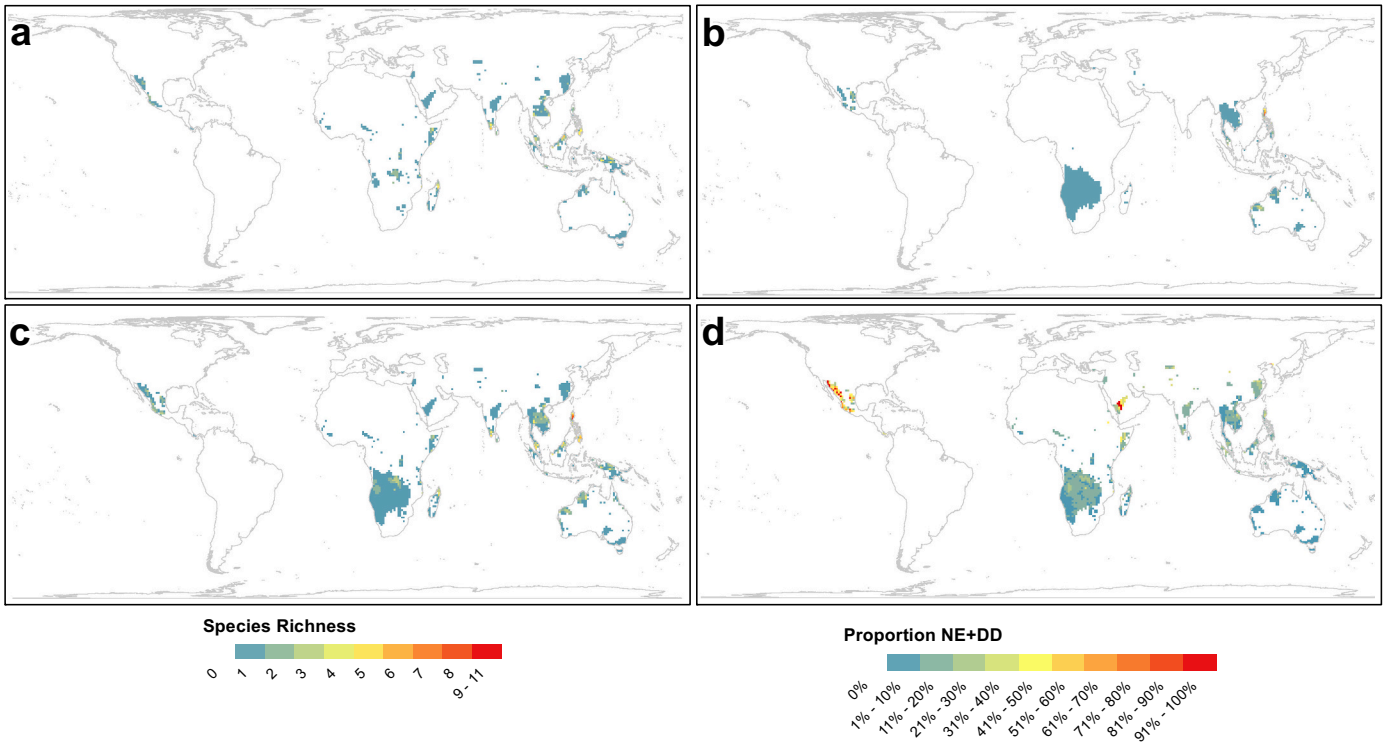

Fig. 4. Species richness of skinks (Scincidae) listed as (A) Data Deficient, (B) Not Evaluated, or (C) non-classifiable (i.e. DD + NE), and (D) proportion of non-classifiable species out of all skink species.
Data from Global Assessment of Reptile Distributions (GARD; http://www.gardinitiative.org/), 2019.

were found to have decreasing populations, with the key threats to skinks identified as agriculture, invasive species, and biological resource use. Using a conservative protected area definition (IUCN Categories I–IV), 61% of species did not overlap a single protected area. Despite our improved knowledge of the conservation status of the world's skinks, a substantial 'assessment gap' remains (e.g., Meiri and Chapple, 2016), with 8% of species yet to be assessed against IUCN Red List criteria. When combined with the 14% listed as Data Deficient, the conservation status of almost a quarter of the world's skink species remains unknown. Below we elaborate on the findings of our study, and outline priorities for the conservation assessment and management of the world's skinks.

4.1. One in five skink species threatened with extinction

We found that ~20% (optimistic-pessimistic range ~16–36%) of the world's skink species are currently threatened with extinction. This level of threat is consistent with the global average for reptiles (~18–19%, Böhm et al., 2013; IUCN, 2020), and less than that documented for reptiles in Madagascar (39%, Jenkins et al., 2014), but substantially higher than that reported for squamate reptiles in Australia (7.1%; Tingley et al., 2019; Chapple et al., 2019) and South Africa (5.4%, Tolley et al., 2019). Relative to other terrestrial vertebrate groups, the proportion of threatened skink species is greater than that reported for birds (14%), but, if most DD species are safe, lower than that recorded for mammals (25%) and amphibians (41%) (IUCN, 2020). Importantly, data reveal that nine skink species are now listed as extinct (either EX or EW). Slavenko et al. (2016) reported that skinks accounted for 45% (20 of 45 species) of lizard extinctions that have occurred during the late Quaternary, with most of these occurring in the Caribbean. As the IUCN only considers species that have gone extinct since 1500, the number of extinct skink species reported here is likely conservative. Indeed, 18 skink species (*Alinea lanceolata*, *Capitellum mariagalantae*, *C. metallicum*, *C. parvicruzae*, *Mabuya cochonae*, *M. grandisterrae*, *M. guadeloupae*, *M. hispaniolae*, *M. mabouya*, *M. montserratae*, *Oligosoma infrapunctatum*, *Spondylurus anegadae*, *S. haitiae*, *S. lineolatus*, *S. magnacruzae*, *S. martinae*, *S. monitae*, *S. spilonotus*) are currently listed as Critically Endangered (possibly extinct). The last confirmed sighting of these species varies from 1830 to 2000 (mean 1924 ± 13 years; see Meiri et al., 2018). Thus, further field surveys of these species will likely reveal that the true number of extinct skink species is higher than that currently reported.

Agriculture, invasive species, and biological resource use represent the three main threats to the persistence of skink species worldwide. Two of these processes, agriculture and biological resource use, also represent key threats to reptiles more broadly (Böhm et al., 2013). We found that the impacts of agriculture on skinks were most pronounced in Madagascar, Australasia (including New Zealand and New Caledonia), and Indo-Malay (Fig. 5a). This detrimental impact of agriculture has previously been reported for Australian squamates (Tingley et al., 2019; Chapple et al., 2019) and African reptiles (Tolley et al., 2016). Similarly, we found that biological resource use effects on skinks (e.g., hunting and collecting of animals; logging and wood harvesting) were most pronounced in Madagascar and south-east Asia (Fig. 5c), which is consistent with previous reports of high rates of biological resource use impacting reptiles in these regions (Böhm et al., 2013; Jenkins et al., 2014). The impact of invasive species on skinks appears to be greatest in Australasia (Fig. 5b), which is supported by several regional reptile assessments that have highlighted invasive species (e.g., invasive mammals, cane toads, weeds; Woinarski et al., 2018) as a key correlate of elevated extinction risk in Australia (Tingley et al., 2019; Chapple et al., 2019), and New Zealand (Tingley et al., 2013). Some of the four secondary threats that were identified for skinks globally (residential and commercial development, natural systems modifications, energy production and mining, climate change), have previously been identified as threats for reptiles globally (urban development, natural resource modification; Böhm et al., 2013), and for Australian squamates (natural systems modifications, energy production and mining, climate change; Tingley et al., 2019). Thus, the threats to skinks are consistent with those reported for

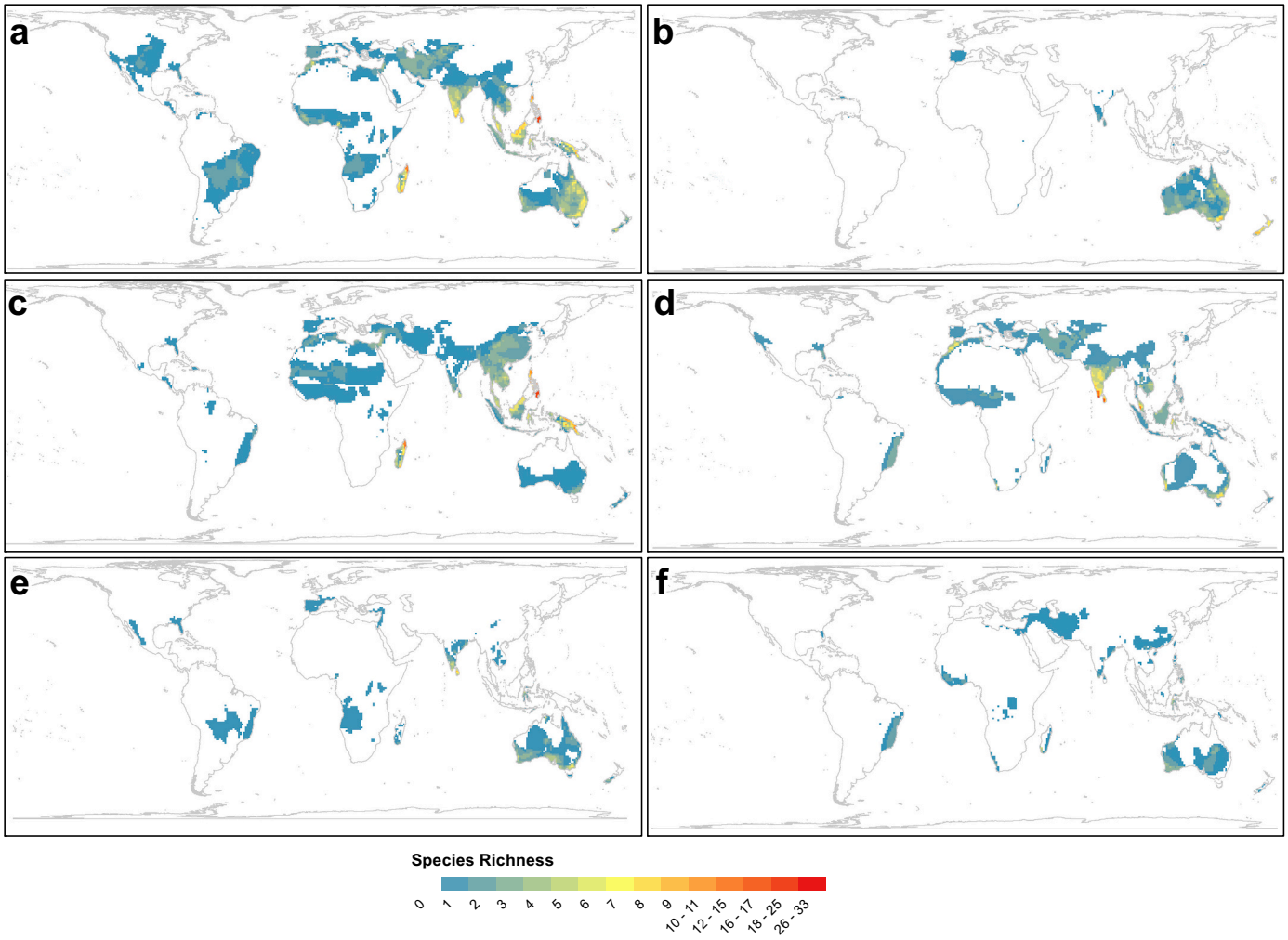

Fig. 5. The distribution of species threatened by each threat type: (A) agriculture, (B) invasive species, (C) biological resource use, (D) residential and commercial development, (E) natural systems modifications, and (F) energy production and mining.
Data from GARD (http://www.gardinitiative.org/), 2019.

Table 5
Number and percentage of species' ranges that do not overlap a single protected area.

IUCN category	Species not in strict nature reserves	Percentage not in strict nature reserves	Species not in reserves set aside for nature	Percentage not in reserves set aside for nature
Critically Endangered	65	89.0	46	63.0
Endangered	77	76.2	67	66.3
Vulnerable	68	75.6	55	61.1
Near Threatened	64	84.2	38	50.0
Least Concern	765	76.5	576	57.6
Data Deficient	190	88.4	149	69.3
Not Evaluated	96	95.0	72	71.3

reptiles more broadly on both local and global scales.

Worryingly, we found that protected areas offer little reprieve from the aforementioned threats, with 61% (IUCN categories I–V) to 80% (IUCN categories I) of species not known to occur in a single protected area. These figures are much higher than reported for Australian squamates (Tingley et al., 2019) and South African reptiles (using interpreted distribution rather than EOO; Tolley et al., 2019). Lack of overlap with protected areas may be underestimated in some rare cases when using species' extent of occurrence maps (such as those used here), due to spatial inaccuracies in defined range boundaries. However, extent of occurrence maps can also overestimate protected area coverage because such maps overestimate true species' distributions (Jetz et al., 2008). The relative magnitude of these two types of errors remains unknown, as densely sampled point locality data, and area of occupancy maps, are unavailable for squamates globally. Our results indicate that the global protected area network is currently insufficient to conserve most skink species.

4.2. Taxonomic and geographic biases

There was clear evidence of bias in extinction risk (e.g., percentage of species threatened, Red List Index) among skink subfamilies, with no

threatened species in Acontinae and Lygosominae, but >25% of species in three other subfamilies (Eugongylinae, Mabuyinae, Scincinae) being listed as threatened (Table 1). Different taxa often vary in key intrinsic (e.g., body size, life history, habitat use and preferences) and extrinsic traits (e.g. geographic range size) linked to extinction risk (Böhm et al., 2016). This could explain why taxonomic biases in threat are regularly reported in vertebrates (Böhm et al., 2013; Tolley et al., 2016; Ducatez and Shine, 2017; but see Tingley et al., 2019). Indeed, the Acontinae have a distinctly different morphology and ecology compared to most other skink subfamilies, with all members completely limbless and having a fossorial lifestyle (Pianka and Vitt, 2003; Greer, 2007; Uetz et al., 2020). Many members of the Lygosominae also exhibit limb reduction and are fossorial (Meiri, 2018; Uetz et al., 2020). However, unlike Acontinae, Lygosominae, whilst overall a small subfamily (54 species), had a high proportion of Data Deficient and Not Evaluated species (41%; Table 1); therefore, the low extinction risk for this subfamily could merely reflect a lack of knowledge rather than the absence of threat.

Geographic biases in the extinction risk (e.g., percentage of species threatened, Red List Index) of skinks were evident, with threat hotspots (>40% threatened species) in the Neotropics and Madagascar, and lower threat levels in the Afrotropics, Indomalayan, Palaearctic, Nearctic, and Australasian regions. These threat hotspots have previously been identified in global (Böhm et al., 2013), and regional (Jenkins et al., 2014), reptile conservation assessments. Indeed, these regions generally have high mean EDGE scores (Fig. S2a). Conversely, whilst previous reptile assessments have identified Australia as having below average levels of extinction risk (Tingley et al., 2019), contrary to our findings, a previous global analysis identified the Oriental and Afrotropical realms as conservation hotspots (Böhm et al., 2013). Interestingly, the overall low level of threat in the Australasian realm may reflect the large number of skink species (27% of the global tally), and relatively low level of threat (also see Tingley et al., 2019) in Australia, obscuring the high threat level that is evident in New Zealand (74% of species threatened, $n = 50$; also see Tingley et al., 2013) and New Caledonia (57% species threatened, $n = 68$). Thus, in some instances, a finer scale analysis is required to identify geographic bias in threat among skinks.

4.3. Skink conservation hindered by a lack of knowledge

We lack detailed knowledge on many skink species, with 14% of assessed species listed as Data Deficient. The dearth of information available for many skink species is further exemplified by the fact that the vast majority (~95%) are listed under Criteria B and D2 (geographic range size), and population trends are unknown for ~43% of assessed species. Thus, the true conservation status of the world's skinks may actually be worse than that presented in this analysis. Indeed, Saha et al. (2018) reported that reptile populations had decreased by ~55% over the past 50 years. However, Bland and Böhm (2016) estimated that ~19% of Data Deficient reptiles are likely to be threatened, which represents roughly the same threat level that has been reported for both reptiles more broadly (Böhm et al., 2013), and skinks (this study). However, Meiri (2016) reported that lizard species described in the 21st Century are more likely to have smaller geographic ranges and are more likely to be threatened. Gumbs et al. (2020) found that Data Deficient species group with threatened species in terms of range sizes, irreplaceability, and phylogenetic uniqueness – and that when ranking threats to reptiles independently of the IUCN process, Data Deficient species were among the most threatened. Thus, as our study finds that skink species that are yet to be assessed against Red List criteria have been described relatively recently (Table 4), and that a substantial number are listed as Data Deficient, the proportion of threatened skink species might actually be higher than we report here. Taxonomic and geographic biases are also evident for non-classifiable (i.e. Data Deficient and Not Evaluated species) skink species. Such species are more likely to occur in Africa and south-east Asia, and are more prevalent in Lygosominae (41%), Scincinae (27%) and Sphenomorphinae (23%). Thus, much research is still required to redress these knowledge gaps that are evident in skinks and this represents a key priority in order to better inform conservation management of the group.

4.4. A lingering 'assessment gap' and the need for re-assessments

The IUCN's first Global Reptile Assessment (GRA) has been responsible for bridging the 'assessment' gap in skinks, decreasing the number of unassessed species from 66% in 2016 (1046 of 1588 species, Meiri and Chapple, 2016) to just 8% in 2020 (136 of 1714 species, this study). But whilst the first GRA has recently concluded (though not yet published), much work remains to be done in order to ensure that all described skink species are assessed against Red List criteria. Firstly, the IUCN recommends that Red List assessments are updated every ten years (IUCN, 2020). As of July 2020, 9% (145 species) of skink assessments are already older than ten years, and a further 12% (190 species) will reach this timepoint over the next three years. Second, ~20 new skink species are described each year (Fig. 2; Uetz et al., 2020). Whilst some of these new species represent newly discovered species, many are the result of the splitting of existing species complexes into two or more species, making the assessments of the "parent" species immediately obsolete. For example, Singhal et al. (2018) conducted a taxonomic revision of three skink species in North Queensland, Australia, splitting *Lampropholis coggeri* (into *L. coggeri*, *L. similis*, *L. elliotensis*), *L. robertsi* (into *L. robertsi*, *L. bellendenkerensis*) and *Carlia rubrigularis* (into *C. rubrigularis*, *C. crypta*) into multiple species. This requires both the assessment of the conservation status of the four new species, but also re-assessment of the three species from which the new species were split (Chapple et al., 2019). Unfortunately, the GRA process has not fully kept track of the species impacted by such species descriptions, and thus we currently have a poor understanding of how many skink assessments have been rendered prematurely obsolete by this taxonomic activity. Finally, 14% of assessed skink species are assessed as Data Deficient. These species are missing from many efforts to conserve biodiversity as we have insufficient knowledge to assess their risk of extinction or apply conservation efforts. Thus, such species would ideally be re-assessed more frequently than every ten years to determine whether our knowledge has improved to the extent that an appropriate Red List category can be assigned. Over the next three years, some form of assessment activity is needed for ~782 skink species (136 Not Evaluated, 335 re-assessments, ~60 new species, ~30 species impacted by taxonomic activity, 221 Data Deficient species; 55% of the entire known diversity).

5. Conclusions

Given the context outlined in this study, the IUCN SSC Skink Specialist Groups' (SSG) goal of attaining up-to-date assessments for all described skink species represents an ambitious target. However, this goal constitutes a vital first step in improving the conservation management of the world's skinks, as it provides essential knowledge and information on extinction risk, in the universal 'language' (i.e. IUCN Red List) used by conservation biologists worldwide. In order to achieve this goal, the SSG aims to (i) assess all Not Evaluated species within the next three years, (ii) assess newly described species, and re-assess species impacted by taxonomic activity, within 12 months of the species description, (iii) re-assess Data Deficient species every 3–5 years (rather than ten years), and (iv) ensure that all skink species are assessed at least once every ten years.

The SSG has a worldwide team of global experts (~160 members, assisted by volunteers) to assist in achieving this goal. In addition, the SSG has clearly outlined key information that it recommends be included in taxonomic papers to facilitate the rapid Red-Listing of newly described species (Fig. 6). This includes 1. A clear description of the

Fig. 6. A summary of the key information that the IUCN SSC Skink Specialist Group has recommended to be included in each taxonomic paper to facilitate the rapid Red Listing of newly described skink species.

species distribution, and estimates of range size such as extent of occurrence (the area of a minimum convex polygon around all known localities, which can be calculated using online tools, e.g., http://geocat.kew.org/), and the number of unique locations (which can be used to calculate area of occupancy, according to the IUCN guidelines this is the number of 2 × 2 km cells occupied by a species). 2. A list of potential threats to the species. 3. Population trend, if known (decreasing, stable, increasing or unknown). 4. A clear summary of the distribution of each species. 5. A summary of the species' general ecology (e.g., diel activity rhythm, diet and foraging strategy), life history (e.g., fecundity, reproductive mode), habitat (e.g., tropical rain forest, desert etc.), and microhabitat preferences (e.g., fossorial, arboreal, terrestrial). 6. A recommended Red-List category (Fig. 6). Complete assessment of all skinks can provide the necessary starting point from which to facilitate the other core roles of the SSG, namely to (i) co-ordinate conservation management for threatened skink species worldwide; (ii) foster collaborative research on skinks, including studies of the factors influencing their extinction risk; (iii) promote priority research actions on Threatened and Data Deficient skink species; and (iv) initiate and facilitate communication and collaboration among skink researchers and conservation managers worldwide.

CRediT authorship contribution statement

DGC, RT and SM conceived the project idea based on the work of the members of the IUCN SSC Skink Specialist Group and GARD group. DGC, RT, SM, UR and MB conducted the analyses. DGC, RT and SM wrote the manuscript. All co-authors provided comments and input into the manuscript.

Declaration of competing interest

We have no competing interests to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2021.109101.

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