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Skinks in Zoos: A global approach on distribution patterns of threatened Scincidae in zoological institutions

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ABSTRACT

To manage populations of threatened species according to the IUCN's One Plan Approach, knowledge about both *in situ* and *ex situ* populations is required. To enhance the conservation of threatened skinks and to gain an overview which skink species are kept in zoos, and thus already have an *ex situ* conservation component, we analysed data from the Zoological Information Management System (ZIMS): their individual numbers, breeding success, and the number of holding institutions. We categorised species as threatened or non-threatened based on IUCN Red List assessments. Only 92 (~5%) of 1727 recognized skink species are held in ZIMS institutions worldwide, mostly in Australia, Europe, and North America. 77% of the species kept globally are classified as non-threatened and ~23% (21 species) are threatened. Only 28% of the species kept have successfully bred in the last year, mostly in one zoo each. Of these seven species were threatened. All threatened species are kept by four zoos at most, generally only in one. Half of the skink species kept are represented by less than 10 individuals. Mainly Australian skink species were kept. To improve the conservation of threatened skinks, a shift towards keeping threatened species should be considered within captive management programmes. European and North American zoos offer capacities and expertise for skink conservation but are outside skink species richness hotspots. Cooperative projects with institutions and stations in such hotspots could greatly benefit the conservation of skinks. Thus, according to the One Plan Approach, the *ex situ* populations could directly contribute to *in situ* protection.

1. Introduction

Modern zoos can play an important role in both *ex situ* and *in situ* conservation of threatened species. They can serve as financial supporters for *in situ* and *ex situ* species conservation projects, not only by investing their own resources (Gusset and Dick, 2010), but also by drawing the public's attention to these problems, and thus promoting their support through donations (Colléony et al., 2017). Through their expertise, capacity, and resources, they can protect and enhance natural populations, and save species from extinction

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by maintaining and breeding *ex situ* populations and initiating subsequent reintroduction programmes (e.g., Scheele et al., 2021; Ziegler et al., 2021). *Ex situ* conservation breeding can be especially important in cases of immediate threats such as disease outbreaks (e.g., the chytrid fungi in amphibians), invasive species natural catastrophes, political unrests or other destructive events (e.g., Amphibian Ark, 2021; Byers et al., 2013; Jacken et al., 2020). Zoos further provide great research opportunities, which can improve knowledge of poorly known species, and lay the foundation for husbandry and reproduction (Conde, 2013; Conde et al., 2011; Fa et al., 2014; Miller et al., 2004). Through the One Plan Approach of the International Union for Conservation of Nature (IUCN) Species Survival Commission (SSC) Conservation Planning Specialist Group (CPSG), the *in situ* and *ex situ* populations are considered as a whole population and all responsible parties work together to develop a conservation plan (Conservation Planning Specialist Group (CPSG), 2021). Among the potential benefits of the One Plan Approach and intensive population management, Byers et al. (2013) list securing populations against imminent threats, studying populations to develop monitoring or management techniques, and programmes that protect juveniles from high mortality and promote population growth.

Skinks (Scincidae) are a diverse family of terrestrial vertebrates. With 1727 recognised species, skinks make up about a quarter of the known lizard (Sauria) species (7059 as of May 2021) and are thus the most species-rich family of lizards (Uetz et al., 2021). However, little is known about the role zoos play or can play in their conservation. In addition to their nearly global distribution, skink species occur in high numbers in species richness hotspots commonly known for lizards (Roll et al., 2017). The highest species richness of skinks is in Australia, New Guinea, Southeast Asia, Sub-Saharan Africa, and Madagascar (Chapple et al., 2021). Their wide distribution is reflected by their ecological diversity and the great variety of their habitats. Some skink species inhabit deserts, others live in rainforests, oceanic islands, and high mountain regions (Greer, 2007). Many species of skinks are threatened with extinction. Saha et al. (2018) estimated that globally about 55% of reptile populations declined between 1970 and 2012. Furthermore, 20 out of 45 documented extinct lizard species (~44.4%) in the late Quaternary are skinks (Slavenko et al., 2016). Slavenko et al. (2016) showed that extinct species were mostly island-endemic. About 13% (210 species at the time of that study) of all skink species are known only from their type locality (an area with a maximum latitudinal and longitudinal range of 10 km) and a further 72 species were last seen alive when their holotype was described (Meiri et al., 2018). Thus, the threat status of skinks can only be assessed to a certain extent so far, as insufficient data are available for many species. This makes the assessment for some skink species according to the IUCN Red List of Threatened Species difficult. Reptiles form the largest group of terrestrial vertebrates, and the least-well assessed: ~28% unassessed species (and a further ~10% assessed as Data Deficient) out of about 11,600 known species (as of May 2021 (IUCN, 2020; Uetz et al., 2021)). The Global Reptile Assessment project in recent years has begun to fill this gap (NatureServe, 2021). For skinks in particular, the establishment of the IUCN Skink Specialist Group (SSG) in 2018, a global network of biologists and wildlife managers with over 160 members actively involved in skink research, was an important step towards filling knowledge gaps and protecting skinks (Skink Specialist Group, 2021). The objectives of the SSG are, on the one hand, to monitor and update the Red List assessments for all skinks and thus to obtain an overview of the endangerment of skink species (Chapple et al., 2021). In this way, the threat factors and threatened species are to be identified. On the other hand, the SSG aims to coordinate the conservation management for threatened skink species and to develop strategies for the protection of the threatened skinks (Chapple et al., 2021).

The current conservation status of skinks, including the distribution of species extinction risk, as well as the main threats to skink populations, have recently been studied (Chapple et al., 2021). Some 92% of the known skinks have been assessed against the IUCN Red List criteria (though many of these assessments remain unpublished, and some are greatly outdated) of which 63% have been assessed as non-threatened, about 16% as threatened and 13% as Data Deficient. Furthermore, the ranges of about 61% of skink species do not overlap with any single protected area. Chapple et al. (2021) identified agriculture, invasive species, and the use of biological resources as the main threats to skink species. While protecting species in their natural habitat is always a priority, some species may also require supportive conservation efforts *ex situ*. *Ex situ* populations can be of use in species conservation, for example by giving time to address the reasons why the species is at risk, such as habitat loss, invasive species or disease outbreak (IUCN Species Survival Commission, 2014). Through reintroduction, *ex situ* populations can offset the effects of threats and reinforce or even restore impacted wild populations.

While charismatic, large vertebrates are favoured by visitors (Colléony et al., 2017), many species-rich groups, including reptiles, are under-represented in most zoos (Conde, 2013). Here, zoo data base analyses can help to point to conservation priorities (e.g., Ziegler et al., 2016, 2017; Jacken et al., 2020). As a first step towards further conservation plans for skinks, this study aims to create a first survey of current skink populations in zoos. The objective is to determine where skinks are kept, which species are kept (and where from), and determine their captive populations size. We further assess whether threatened species are better represented than non-threatened species in terms of the number of holdings, the breeding success, and the number of individuals. It is the ambition of this study to identify improvements in the composition of *ex situ* holdings of skinks to better implement the *ex situ* conservation component according to IUCN's One Plan Approach.

2. Methods

2.1. Species holding data

A list of all currently recognized skink species (and their respective subfamilies) was downloaded from the Reptile Database (Uetz et al., 2021) on 14th December 2020. We analysed the available data of skink holdings in the Zoological Information Management Software (Species360 Zoological Information Management Software (ZIMS), 2020) matching names to the Reptile Database. The dataset was downloaded between 15th and 16th December 2020. It contains the number of individuals kept, the number of institutions reporting current holdings, and reports of successful reproduction within the past 12 months for each species. Not all zoos subscribe to

ZIMS, or record their holding data in the database. In addition, some entries in ZIMS may be obsolete or current data might not yet have been entered. The ZIMS zoo-region labelled 'Australia' comprises the land region of Australia and Oceania.

In order to analyse additional holdings, we also searched the website "Zootierliste" (ZTL, Zoo Animals' list (Graf et al., 2020)). The ZTL is a database in which current and former animal holdings of European zoos, and other public animal holdings, are entered and updated by registered users. The ZTL does not contain information on the number of individuals or breeding success. Data from the ZTL were only included in an analysis of current species holdings to get a most complete species inventory. All further analyses are based only on the data retrieved from ZIMS. Taxonomy follows the Reptile Database (Uetz et al., 2021).

2.2. Conservation status

The extinction risk assessments for all species were downloaded on 21st December 2020 from the IUCN Red List of Threatened Species (IUCN, 2020). The species were divided into three threat groups according to their IUCN Red List status. Species assessed as Vulnerable (VU), Endangered (EN) or Critically Endangered (CR) were grouped together as 'threatened' species. The Red List Categories Least Concern (LC) and Near Threatened (NT) were grouped together as 'non-threatened' species. The third group, named 'non classifiable', comprised species listed as Data Deficient (DD) or Not Evaluated (NE). No species listed in ZIMS were assessed as Extinct (EX) or Extinct in the Wild (EW). For 20 species, the IUCN Red List categories were updated by future assessments not yet published in the IUCN's Red List (from Chapple et al., 2021). This allowed the non-classifiable to be dissolved. ZIMS holding entries that were only determined to the genus level were omitted because no IUCN Red List status could be assigned to them, and they could also represent different species. Subspecies entries were also omitted, as the IUCN assesses skinks at the species level.

Data processing was carried out with R version 4.0.2 (R Core Team, 2020) and the R packages 'reader' (Wickham et al., 2018), 'xlsx' (Dragulescu and Arendt, 2020), 'dplyr' (Wickham et al., 2020). The packages 'ggplot2′ (Wickham, 2016), 'ggpattern' (Mike, 2021), and 'scales' (Wickham and Seidel, 2020) were used for visualisation of plots.

We compared the proportion of threatened amphibians in zoos with the proportion of threatened zoo-kept skinks using a chi-square test. Furthermore, the distributions of traits between threatened and non-threatened species were examined for randomness. For this purpose, 10,000 random sample sets were drawn from the available zoo data in R and 99% confidence intervals for the randomised occurrence of the trait were calculated (bootstrap approach).

2.3. Species richness analysis

In order to investigate possible species richness patterns, the range maps of all species reported by ZIMS institutions were downloaded from the IUCN Red List website on 11th February 2021 (IUCN, 2021). Data from georeferenced field points for species with no distribution data available from the IUCN were retrieved from gbif.org, also on 11th February (GBIF.org, 2021a-x). The GBIF data were cleaned of subspecies records, and for the IUCN data records of introduced and reintroduced locations were removed. Distribution data of five remaining species were added from the GARD database (Gumbs et al., 2020). For each of the six continental zoo regions (Africa, Asia, Australia/Oceania, Europe, North America, and South America), overlays of the natural ranges of all skinks kept in each region were computed using the raster (Hijmans, 2020), and shapefile packages (Stabler, 2013), for R version 4.0.2 (R Core Team, 2020) with a spatial resolution of 2.5′. Maps were visualised in QGIS (QGIS Development Team, 2021).

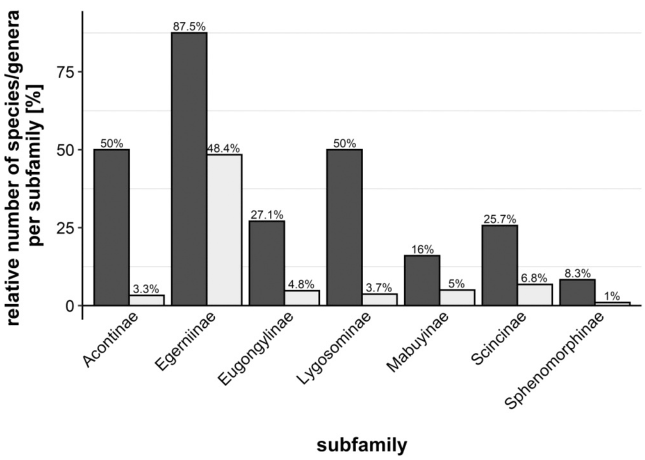

Fig. 1. Relative number of species or genera listed in ZIMS (2020) from the currently described species/genera (according to Uetz et al., 2021) per subfamily. The percentage of skink genera (dark grey) and skink species (light grey) kept in zoos of all described species or genera for each subfamily.

3. Results

3.1. Distribution of records

Of the 53 skink species listed only in ZIMS, 16 were assessed as threatened by the IUCN and 37 species as non-threatened. All 11 species listed only on the ZTL were assessed as non-threatened. The 39 species present in both databases consisted of five threatened species and 34 non-threatened species (see Supplementary Material Table S1-S3 for all species listed). Only species present in ZIMS (including species that were present in both databases: n = 92) were used in further analyses.

ZIMS reported 844 skink holdings: 318 by North American zoos, 302 by European zoos, 188 by Australian zoos, 28 by Asian zoos, four by African, and four by South American zoos. With 49 species, Australian zoos kept the largest number of species, followed by Europe (46), North America (29), Asia (11), Africa (4), and South America (2). Fifteen threatened species were kept in Australian zoos, five in European zoos, one in Asian zoos, one in African zoos, and no threatened species were kept in North or South American Zoos.

3.2. Phylogenetic Representation

The 92 skink species held in ZIMS institutions worldwide represent only 5.3% of the 1727 skink species recognized (Uetz et al., 2021). Most zoo-kept genera and species belonged to the subfamily Egerniinae (seven of eight described genera: 87.5%, 30 of 62 of species: 48.4%; Fig. 1). The Acontinae were represented by 50% of genera (one out of two) but only 3.3% (1 out of 30) of its species. Two of four Lygosominae genera were represented in zoos, but only 3.7% of the known species were (two out of 54 species). In the Eugongylinae, 13 of 48 genera were represented in zoos (27.1%) and 22 of the 454 described species of the subfamily (4.8%). Nine out of 35 genera (25.7%) of the Scincinae were represented in zoos and included 20 out of 295 species (6.8%). Four of 25 Mabuyinae genera (16%) and 11 out of 222 species (5%) were kept in zoos. The most species-rich subfamily, the Sphenomorphinae, was strongly underrepresented in zoos. Only three out of 36 genera (8.3%) and six out of 592 species (1%) were kept in zoos.

3.3. Distribution of skinks in IUCN Red List Categories in zoos

72.8% of the species kept in zoos were assessed as Least Concern (Fig. 2a), with a further 4.4% listed as Near Threatened and 22.8% (21 species) as threatened (6.5% Vulnerable, 9.8% Endangered and, 6.5% Critically Endangered). Currently kept threatened species, as well as their individual and holding numbers and the number of offspring are listed in Table 1.

The distribution of the Red List Categories of all described skink species worldwide has recently been studied (Chapple et al., 2021). The 1705 skink species analysed by Chapple et al. (2021) were distributed similarly among the categories as the species kept in zoos (Fig. 2b). Most skink species are non-threatened (63.6%), 15.5% are threatened and 20.9% have either not yet been assessed or have been assessed as Data Deficient. No Data Deficient or Not Evaluated species were kept in zoos. Of the 73 skink species classified as Critically Endangered, only six are kept in zoos (Table 1). Thus, no *ex situ* populations of 67 Critically Endangered Species are found in ZIMS institutions (Table 2). 92 of the 101 species listed as Endangered and 84 of the 90 species listed as Vulnerable are not kept in ZIMS institutions (Supplementary Material Tables S4–S5).

3.4. Breeding success in zoos

28.3% of the species kept were reported to have bred successfully in the last 12 months (only ~10% of skink species breed less than once or twice a year (Meiri, 2018); thus a higher number of species kept in zoos would be expected to breed). Seven of the 21

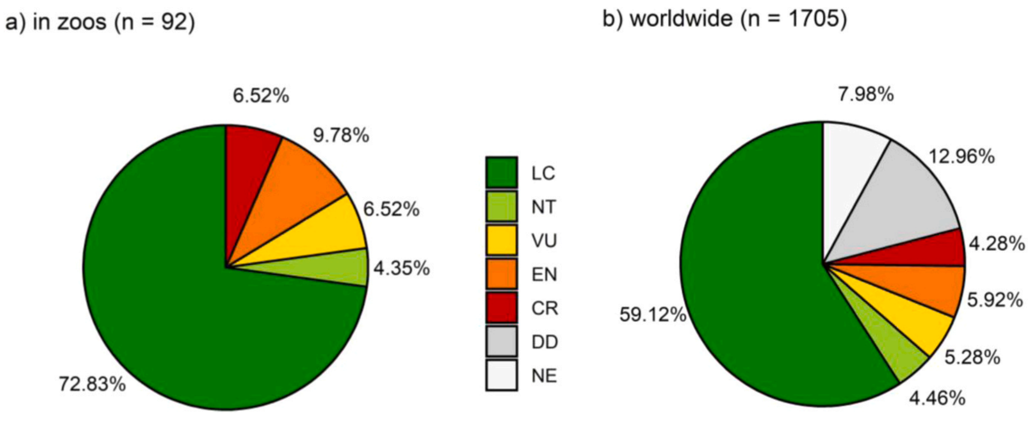

Fig. 2. Distribution of IUCN Red List Categories of a) skinks kept in zoos (n = 92; according to ZIMS (2020)) and b) skinks worldwide (n = 1705; according to Chapple et al. (2021)). Species evaluated as Extinct (in zoos: 0; worldwide: 8) or Extinct in the Wild (in zoos: 0; worldwide: 1) were excluded.

Table 1
Threatened skink species kept in ZIMS institutions (n = 21). Pop. Trend: Population Trend (IUCN, 2020): ↓ decreasing, ↑ increasing, → stable, ? unknown. Number of Individuals: M: male, F: female, U: unsexed. Offspring in the past 12 Month. Origin: Region of origin; Au: Australia or Oceania, Af: Africa, NA: North America. * Species could be misidentified as this one has not been recorded for ~130 years.

Subfamily Species	IUCN Status	Pop. trend	Individuals (M/F/U)	Institutions	Offspring	Origin
Egerniinae						
Cyclodomorphus praealtus	EN	↓	6 (2/1/3)	1	0	Au
Liopholis guthega	EN	↓	12 (2/10/0)	1	0	Au
Liopholis kintorei	VU	↓	4 (1/1/2)	1	0	Au
Liopholis slateri	VU	↓	25 (5/5/15)	1	2	Au
Tiliqua adelaidensis	EN	↓	15 (9/2/4)	4	0	Au
Eugongylinae						
Lacertoides pardalis	VU	↓	3 (1/1/1)	1	0	Au
Leiolopisma telfairii	VU	↑	17 (8/9/0)	2	0	Af
Oligosoma alani	VU	↑	11 (3/4/4)	1	0	Au
Oligosoma fallai	VU	→	23 (3/4/16)	3	22	Au
Oligosoma grande	EN	→	9 (0/2/7)	2	0	Au
Oligosoma homalonotum	EN	→	13 (2/1/10)	1	6	Au
*Oligosoma infrapunctatum**	CR	?	56 (18/13/25)	1	0	Au
Oligosoma lineoocellatum	EN	↓	1 (1/0/0)	1	0	Au
Oligosoma otagense	EN	↓	14 (4/3/7)	4	0	Au
Oligosoma salmo	CR	↓	62 (20/27/15)	1	11	Au
Mabuyinae						
Chioninia vaillantii	EN	↓	8 (3/3/2)	3	0	Af
Scincinae						
Gongylomorphus bojerii	CR	→	34 (14/16/4)	1	6	Af
Gongylomorphus fontenayi	EN	↓	51 (25/13/13)	1	2	Af
Plestiodon longirostris	CR	↓	27 (4/5/18)	1	6	NA
Scelotes inornatus	CR	↓	8 (0/0/8)	1	0	Af
Sphenomorphinae						
Ctenotus lancelini	CR	?	1 (1/0/0)	1	0	Au

threatened species (Fig. 3) and 19 of the 71 non-threatened species (Supplementary Material Table S6) were successfully bred in zoos. Slightly more threatened species were bred (26.9%) than would be expected from a random selection of the 92 skink species [$p < 0.01$, 99% CI 22.78–23.11%].

Each threatened species breeding was kept in one zoo (Fig. 4), significantly more than expected from a random distribution of these 21 species [$p < 0.01$, 99% CIs: single zoo 61.42–61.72%, 2–4 zoos 19.12–19.37, 5–10 zoos 15.23–15.45, 11–20 zoos 3.78–3.9%]. Of the 26.8% of non-threatened species that bred, 12.7% bred in one zoo, 7% in 2–4 zoos, for 5.6% in 5–10 zoos and 1.4% in more than ten zoos. *Corucia zebrata* bred at 18 institutions: more than any other species.

3.5. Number of holdings for each threat group

Fifteen of the 21 threatened species (71.4%) were kept by only one zoo (Fig. 5). The remaining six threatened species (28.6%) were kept by 2–4 zoos. Threatened species were kept in significantly fewer institutions than would be expected by chance [$p < 0.01$, 99% CIs: single 46.56–46.95%, 2–4 zoos 29.16–29.5%, 5–10 zoos 8.61–8.82%, 11–25 zoos 8.55–8.76%, >25 zoos 6.45–6.64%]. Of the 71 non-threatened species, 28 were kept in only one zoo (39.4%), 21 species (29.6%) in 2–4 zoos, eight species by 5–10 zoos (11.3%) and another eight species by 11–25 zoos (11.3%). Six non-threatened species were kept by more than 25 zoos (8.5%): *Corucia zebrata* (161 institutions). *Egernia stokesii* (31 institutions), *Tiliqua gigas* (53 institutions), *T. rugosa* (62 institutions), *T. scincoides* (182 institutions, the highest number overall) and *Tribolonotus gracilis* (42 institutions).

3.6. Distribution of individuals

3136 skink individuals were kept in ZIMS institutions. Of these 21.2% were identified as males, 19.1% as females and 59.7% were unsexed. Seventeen species (18.5% of the 92 species) kept in zoos were kept exclusively as single individuals or same-sex groups (Table 3). Of two threatened species, only a single individual was kept (9.5% of threatened skink species in zoos). Of the non-threatened species, four species were kept in single-sex, multiple individual groups and only a single individual was kept from 11 species (in total 21.1% of non-threatened species). These numbers might be even larger, as groups of unsexed animals were not counted, but they could turn out to be unisexual.

Of the 92 species, half (46 species) were represented by fewer than 10 individuals in ZIMS institutions (Fig. 6). Between 10 and 49 individuals were kept of 35% of the species, of which 10 were threatened species and 22 non-threatened species. Fifty to 99 individuals from five species (three of them threatened) and 100–199 individuals from five additional species (all non-threatened) were kept. More than 200 individuals were only kept from four species: *Chalcides ocellatus* (275, LC), *Corucia zebrata* (485, NT), *Tiliqua rugosa* (238 individuals, LC), and *T. scincoides* (303, LC). Individual-rich species were significantly less frequent among threatened species than would be expected from a random distribution [$p < 0.01$, 99% CIs: <10 individuals 49.79–50.3%, 10–49 individuals 34.52–34.99%,

Table 2
Critically Endangered skink species which are currently not kept in ZIMS institutions (n = 67). Origin: Region of origin; Af: Africa, Au: Australia or Oceania, MA: Central America, EA: East Asia, SAs: South Asia, SEA: Southeast Asia.

Subfamily	Species	Origin
Egerniinae	*Bellatorias obiri*	Au
Eugongylinae	*Austroablepharus barrylyoni*	Au
	Caledoniscincus constellatus	Au
	Cryptoblepharus caudatus	Af
	Emoia slevini	Au
	Lacertaspis lepesmei	Af
	Leiolopisma alazon	Au
	Lioscincus vivae	Au
	Marmorosphax kaala	Au
	Nannoscincus exos	Au
	Nannoscincus hanchisteus	Au
	Nannoscincus koniambo	Au
	Nannoscincus manautei	Au
	Nannoscincus rankini	Au
	Oligosoma albornense	Au
	Oligosoma awakopaka	Au
	Oligosoma burganae	Au
	Oligosoma hoparatea	Au
	Oligosoma judgei	Au
	Oligosoma pikitanga	Au
	Phoboscincus bocourti	Au
	Sigaloseps ruficauda	Au
Mabuyinae	*Alinea lanceolata*	MA
	Capitellum mariagalantae	MA
	Capitellum metallicum	MA
	Capitellum parvicruzae	MA
	Mabuya cochonae	MA
	Mabuya desiradae	MA
	Mabuya grandisterrae	MA
	Mabuya guadeloupae	MA
	Mabuya hispaniolae	MA
	Mabuya mabouya	MA
	Mabuya montserratae	MA
	Marisora roatanae	MA
	Panopa croizati	MA
	Spondylurus anegadae	MA
	Spondylurus culebrae	MA
	Spondylurus haitiae	MA
	Spondylurus lineolatus	MA
	Spondylurus macleani	MA
	Spondylurus magnacruzae	MA
	Spondylurus martinae	MA
	Spondylurus monae	MA
	Spondylurus monitae	MA
	Spondylurus semitaeniatus	MA
	Spondylurus sloanii	MA
	Spondylurus spilonotus	MA
	Spondylurus turksae	MA
	Trachylepis nganghae	Af
Scincinae	*Barkudia insularis*	SAs
	Brachymeles cebuensis	SEA
	Chalcides ebneri	Af
	Flexiseps valhallae	Af
	Madascincus arenicola	Af
	Nessia layardi	SAs
	Paracontias fasika	Af
	Paracontias minimus	Af
	Paracontias rothschildi	Af
	Pseudoacontias menamainty	Af
Sphenomorphinae	*Ctenotus serotinus*	Au
	Eremiascincus antoniorum	SEA
	Lankascincus deignani	SAs
	Larutia penangensis	SEA
	Lerista allanae	Au
	Lerista nevinae	Au
	Lerista vittata	Au
	Scincella huanrenensis	EA

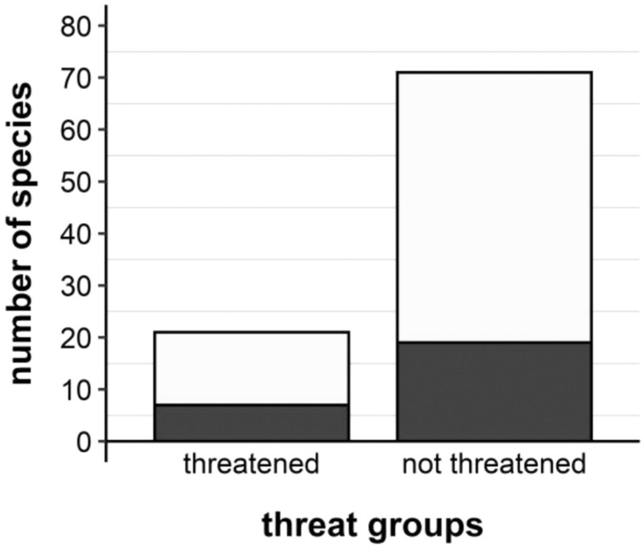

Fig. 3. Number of skink species with and without reported breeding success in ZIMS (2020) institutions within the last 12 months. Species are divided according to their IUCN Red List status (2020). Dark grey: species that have bred in the last 12 months; light grey: species that have not bred in the last 12 months.

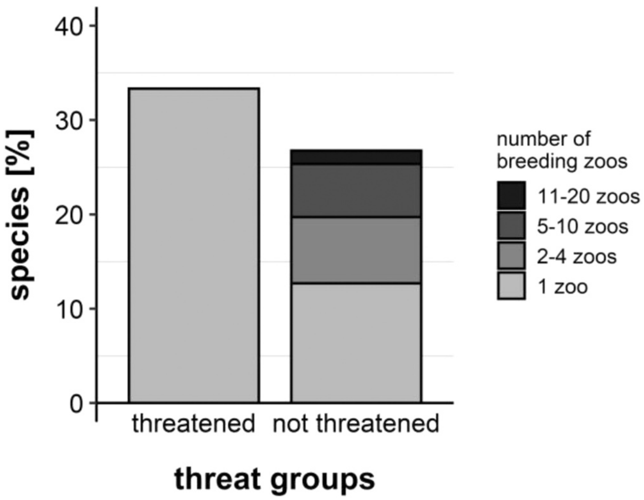

Fig. 4. Percentage of skink species with reported breeding success categorized by the number of ZIMS (2020) institutions that reported success. Breeding success was reported by only a single zoo, two to four zoos, five to ten zoos or eleven to twenty zoos, as shown by the different shades of grey. The species are divided by the two threat groups according to their IUCN (2020) Red List status. The percentages were calculated by dividing the total number of species for a threat group by the number of species in that threat group with reported breeding success for each size group of zoo-keeping numbers.

50–99 individuals 5.31–5.54%, 100–199 individuals 5.3–5.52%, 200–299 individuals 2.14–2.28%, >300 individuals 2.08–2.23%].

3.7. Species richness of zoo skinks

As only two skink species were kept in South American zoos, and four in African zoos, no meaningful geographic analysis could be carried out (see Supplementary Material Fig. S1 for distribution maps of these two regions). Asian zoos mainly kept species (n = 11) from Australia, North Africa and the Middle East (Fig. 7a). Most skink species (49) were kept in Australian zoos, which kept only skink species from Oceania, mostly from Australia and a few from New Zealand, New Caledonia, Solomon Islands, and southern Papua New Guinea (Fig. 7b). European zoos kept species (46) from many different regions, mostly from eastern Australia (Fig. 7c). Furthermore, species from Africa, the Middle East, and south-east Asia were also kept. Species (29) kept in North American zoos originated from different regions, mostly from Western Australia (Fig. 7d). Other species-rich locations were North Africa and eastern Australia. North

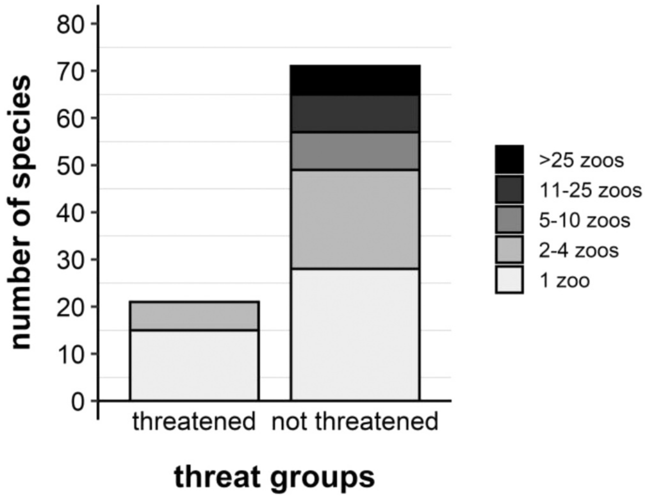

Fig. 5. Classification of skink species according to number of holding ZIMS (2020) institutions. The species are divided by the two threat groups according to their IUCN (2020) Red List status. For each threat group, the skink species were subdivided according to the number of ZIMS institutions holding them, represented by the different shades of grey.

Table 3
Species kept exclusively as single individual or in unisexual groups as listed in ZIMS (2020). The species are divided into subfamilies and genera. Inst.: Number of institutions that kept the species; Thr.: Threat status (NT: non-threatened (species assessed as Least Concern or Near Threatened); Thr.: Threat status (N: non-threatened; Y: threatened); Ind.: Number of Individuals kept single or in a unisexual group (F: Female; M: Male; U: unsexed): individuals of the same species listed in different rows were held in different institutions.

Subfamily	Species	Inst.	Thr.	Ind.
Egerniinae	*Cyclodomorphus casuarinae*	1	N	1 U
	Egernia formosa	1	N	2 M
	Tribolonotus novaeguineae	2	N	1 M
				1 F
Eugongylinae	*Morethia ruficauda*	1	N	1 F
	Oligosoma lineoocellatum	1	Y	1 M
	Phasmasaurus tillieri	1	N	1 F
	Sigaloseps deplanchei	1	N	1 U
	Tropidoscincus variabilis	1	N	1 F
Mabuyinae	*Trachylepis. varia*	1	N	1 M
	T. sulcata	1	N	1 M
Scincinae	*Brachyseps macrocercus*	1	N	3 F
	Chalcides viridanus	1	N	1 U
	Plestiodon laticeps	3	N	1 M
				1 M
				1 F
Sphenomorphinae	*Ctenotus brooksi*	1	N	1 M
	C. lancelini	1	Y	1 M
	Eulamprus quoyii	1	N	1 M
	E. tympanum	1	N	1 U

American zoos were the only zoos that kept species from America, specifically from North America.

4. Discussion

4.1. Representation of skinks

The proportion of all skink species held in ZIMS institutions represents a small fraction of the described skink species worldwide, at only about 5.3%. Even if other skink species are kept in other institutions that do not contribute to ZIMS (e.g., the 11 additional species listed on the ZTL) this would most likely only be a small increase in relation to the number of extant skink species (1727 species as of May 2020 (Uetz et al., 2021)). The subfamily of Egerniinae, which has a moderate number of species (62 species), is proportionally best represented in zoos, but still less than half of the known Egerniinae species are represented. The most species rich subfamily, Sphenomorphinae (592 species), is heavily underrepresented with only 6 species held in zoos. Of all other subfamilies, less than 10% of the known species are kept.

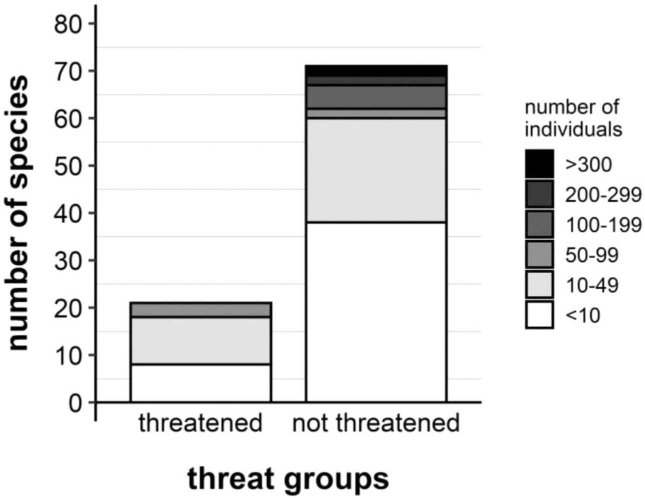

Fig. 6. Number of individuals of the skink species kept in ZIMS (2020) institutions (n = 92). The species are divided by the two threat groups according to their IUCN (2020) Red List status. The greyscale shows the number of species that fall within the range of the number of individuals.

Non-threatened species (LC and NT) account for more than three quarters of the skink species currently held in ZIMS institutions and are thus currently of little relevance for the *ex situ* conservation of threatened species. The proportions of the Red List categories of zoo-kept species are similar to those of the globally known skink species (Chapple et al., 2021). Thus, no trend towards keeping more threatened species can be identified. Many non-threatened species probably do not need *ex situ* and intensively managed zoo populations. They are kept in zoos for entertainment or education, are easy to obtain, transport and keep, show fascinating appearances (e.g., blue-tongued skinks), or are used as flagship species to point out problems. Most of the skink species kept are diurnal (65 species), mainly terrestrial (52), viviparous (52), with adult snout vent lengths ranging from 42 to 391 mm (mean 152 mm), and almost all are four-legged (88), thus exhibiting characteristics that make them interesting and visible to visitors (data of traits from Meiri, 2018; *Gongylomorphus fontenayi* and *Oligosoma salmo* were not included). When comparing skinks kept in zoos versus those not kept, according to an updated version of Meiri (2018), there were no significant differences in activity times or substrate. But skink species held in zoos tend towards herbivory/omnivory (48% of zoo-kept species versus 6% in all skinks) and viviparity (65% of zoo-kept versus 32%). Interestingly, of the 64 largest skinks (by mass) only 11 are not kept in zoos, but the smallest skink kept (*Gongylomorphus fontenayi*) is the 162 smallest of all skinks. Skinks held in zoos also are much more likely to have all their limbs (98% of species) and not be legless or limb reduced (2% together vs. 20% in all skinks). Finally, they are 9 times larger (heavier): 49.2 vs. 5.5 g. All these latter differences were statistically significant.

A number of threatened skink species are not representing good display species in the traditional sense (e.g., small, semi-fossorial, solitary, etc.) and thus do not appeal to a wide range of zoos, because they are not well visible to visitors. For these species, institutions with a greater research / conservation focus are the most suitable. In general, more zoos being part of conservation breeding programs and thereby improving the conservation of threatened skinks, can be achieved by setting aside off-show space, preferably in a biosecure setting - a need for many species but not currently prioritized by most zoos. This needs to change and there is demand for modern, scientifically led zoos to invest in such small but important conservation initiatives in addition to their public exhibits. Such approach would contribute to extend conservation breeding initiatives and represents a chance to increase the number of threatened skink species in *ex situ* programmes, thus substantially improving the One Plan Approach for threatened skink species.

The few threatened skink species kept are only held in few institutions, in small populations, and few are breeding. With a few exceptions, the non-threatened taxa are also rather poorly represented in zoos. To maintain healthy *ex situ* populations, each species should be kept by several institutions. This allows to increase the population size and diversity and to create several safeguard populations against unpredictable events (such as diseases, natural catastrophes, or other destructive events), thus better protecting the whole *ex situ* population (Jacken et al., 2020). The number of skink species exceeding the criterion (more than four holding institutions) suggested by Jacken et al. (2020) is therefore very low: only 22 out of 92 skink species are held in 5 or more zoos. Of the 21 threatened species, only two (*Tiliqua adelaidensis* and *Oligosoma otagense*) reach the minimum of four institutions. Species that are only kept in one or a few institutions should be distributed in several institutions to protect the population.

Nevertheless, it should be noted that some species held only in individual institutions are kept for official reintroduction projects and are on loan from the respective government in the country of origin (e.g., *Gongylomorphus bojerii*, *G. fontenayi* (Ministry of Environment and sustainable Development, 2010)). As governments often do not allow the distribution of animals to institutions other than the direct partner institution, in these cases surplus offspring cannot be simply provided to other institutions. In some other cases, it may not be possible to distribute these animals due to the lack of capacity in other institutions in the country or due to a population being too small for distribution at the beginning of a breeding programme. Other potential partners might be located in adverse climatic zones and therefore unsuitable if the species in question should be held in naturalistic outdoor enclosures, which is often preferred for release projects. In most of the cases above, the mentioned projects entail an eventual release of animals, mandating that

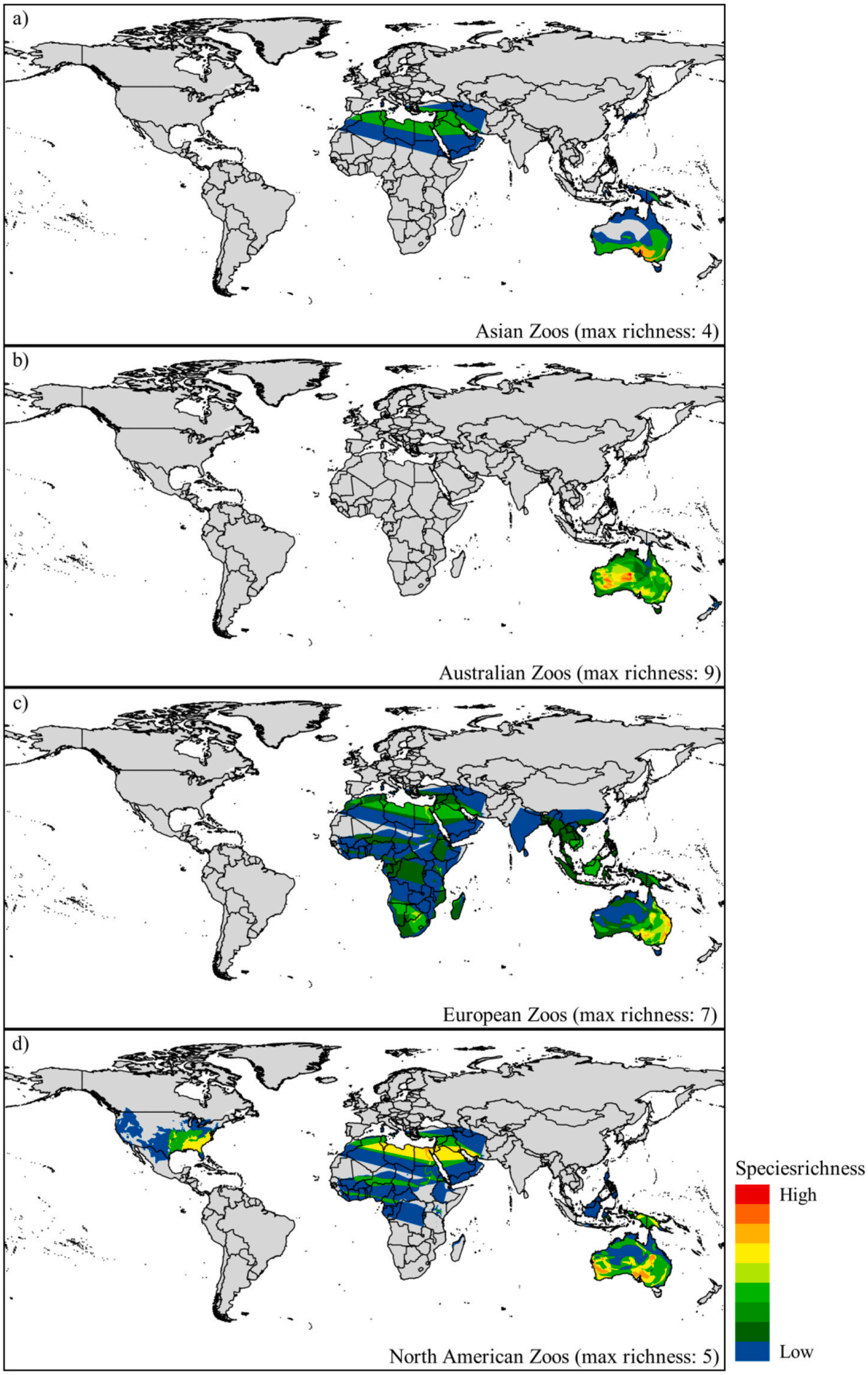

Fig. 7. Distribution of skink species from a: Asian zoos (n = 11); b: Australian zoos (n = 46); c: European zoos (n = 44); d: North American zoos (n = 28). Species in Asian zoos originated from Australia, North Africa, the Middle East and Indonesia. Australian zoos almost exclusively kept species endemic to their region with the highest accumulation in central and western Australia. The highest concentration of species kept in European zoos originated from eastern Australia and other species from Africa, the Middle East and south-east Asia. Most species from North American zoos originated from western and eastern Australia and the Nile Delta. North American zoos were the only zoos keeping species from America.

the respective populations are held in bio-secure facilities. Unfortunately, capacity and attendance to invest in such facilities is still low in zoological institutions, reducing the number of potential partners significantly.

Furthermore, for some species, grouping individuals could be used to build reproductive populations with the existing stocks. By taking in further individuals (e.g., from confiscations or rescued specimens) or exchanging them, and thus jointly protecting *in situ* and *ex situ* populations according to the One Plan Approach, even a small population can be kept viable and contribute to the protection of the species (Byers et al., 2013). In case of unknown origin of confiscated individuals, molecular analyses are a useful tool to identify species properly and even allocate them to certain lineages and geographical regions, which makes them or their offspring suitable for later reintroduction into the wild (e.g., Le et al., 2020; Ziegler et al., 2015; Ziegler and Vences, 2020). Both translocations and reintroductions of skinks have already taken place (e.g., Towns, 2002; Towns and Atkinson, 2004; McCoy et al., 2014; Towns et al., 2016).

A studbook and a species survival plan exist for *Corucia zebrata*, the skink with the highest number of individuals in ZIMS institutions (485 specimens) at the North American Association of Zoos and Aquariums (AZA (2016a) (2016b). This is an example of how, with good management, it is possible to achieve large *ex situ* population numbers, even in species that initially appear complicated to breed, and thus actively contribute to the One Plan Approach by supporting *in situ* populations. Further species management programs exist for *Oligosoma grande,* and *O. otagense* coordinated by the Auckland Zoo, New Zealand (Zoo and Aquarium Association Australasia (ZAA), 2021). In total, only six studbook programmes are listed in ZIMS, five of which have only one current holding institution each (see Supplementary Material Table S7).

Compared to other reptile taxa, skinks are poorly represented in zoos. Thirty monitor lizard species (38%) and only one crocodile species (3.7%) were at the time of investigation not kept in zoos (Ziegler et al., 2016, 2017). In comparison, 94.6% of the described skink species are not yet held in zoos. While the number of skink species described is many times greater than that of monitor lizards (79 species) or crocodiles (27 species) recorded few years ago, most skink species are much smaller than crocodiles and monitor lizards and require less space and effort to keep. A few species of skinks, monitor lizards, and crocodiles (Ziegler et al., 2016, 2017), are widespread and well represented in zoos, while the remaining species are barely represented, with only a few individuals, or not represented at all.

Compared to amphibians, skinks are similarly poorly represented in zoo holdings. About 7.1% (540 of 7658 species at that time) of amphibian species are currently kept in zoos (Jacken et al., 2020). The proportion of threatened amphibian species kept in zoos is low (25.1%), and not significantly higher than for skinks (19.6%; $\chi^2 = 4.41$, df = 2, p = 0.11). Both amphibian and skink species, are often only kept in one zoo. Analyses of reptile taxa of similar size, such as geckos, which is a more comparable reptile group, have not yet been conducted, but respective analyses are currently performed by us.

4.2. Richness analysis of the geographic distribution of skink species

The greatest diversity of species was kept in Australian and New Zealand zoos, even if the number of holdings there was not the highest. These zoos concentrate on keeping native species. Australian zoos held the largest proportion of threatened species, with about a third of the species held. Since only about 7% of Australian squamates are threatened (Tingley et al., 2019), this might indicate that at least in Australian zoos there is a slight preference for keeping threatened species. With both the second highest number of holdings and the second highest number of different skink species kept, European zoos can play an important role in skink conservation with their capacity and expertise. However, the proportion of threatened species kept is also low there. European zoos only keep few species native to the European mainland. However very few skink species inhabit mainland Europe (Roll et al., 2017). There were only a few Asian ZIMS institutions holding skinks, and only few species were kept as well as in African and South American zoos. In these areas, however, fewer institutions might be using ZIMS (e.g., due to costs). For example, the African Association of Zoos and Aquaria (PAAZA, 2021) currently represents 70 institutions, while only 25 African institutions participating in ZIMS (2020) could be found, in which only four skink holdings were listed. Other skink species and husbandries may be present in these non-ZIMS participating institutions. However, the proportion of skink holding African ZIMS institutions is low, which means that no enormous increase in African skink holdings is to be expected from the non-ZIMS institutions.

Overall, the zoos' attention seems to be generally focused on Australian skinks, which may be due to the fact that the highest diversity of skinks is found in Australia and Southeast Asia (Roll et al., 2017). Furthermore, the Australian subfamily Egerniinae, contains many large-bodied skinks which are more attractive for zoo visitors and readily available as they are present since decades especially among European collections and private breeders. Some African species are also represented in European and North American zoos. However, the keeping of Asian, and especially South American and European skinks, is rare or even non-existent.

There are, and have been, several native threatened skink conservation projects by, and with, Australian zoos demonstrating that and how breeding programs for skinks can be successful for species conservation. For example, Zoos Victoria in Australia currently runs two zoo-based captive management programmes to protect native threatened skink species (Scheelings, 2015; Zoos Victoria, 2021): the Guthega Skink (*Liopholis guthega*; EN) and the Alpine She-oak Skink (*Cyclodomorphus praealtus*; EN).

According to the Convention of Biological Diversity, *ex situ* measures should preferably take place in the respective country of origin in order to complement *in situ* measures (Glowka et al., 1994). For the Australian species, this goal seems achievable as there are already many skink-holding institutions with the expertise needed to keep them. Africa and South America, however, are far from this goal, as there are almost no institutions with current skink holdings, and in South America, no native species are kept, according to ZIMS. For both regions, the North American and European institutions offer existing capacities with expertise in skink conservation, while only having a small amount of native skink species. *Ex situ* holdings outside the country of origin can be of great importance in case of problems in the country of origin, such as natural disasters, disease outbreaks, political or social unrest, or lack of expertise, finance, and capacity. For example, there are some long-established collaborative projects between European zoos and institutions in the species' country of origin (Gippoliti, 2012; Ziegler, 2015; Ziegler et al., 2021), and such projects could also be of great use for skink species from South America and Africa.

5. Conclusions

As particularly diverse and the most species-rich family of lizards, skinks can serve as flagship species for the representation of various problems and threats of this group and entire ecosystems and thus draw attention to a large number of threats facing animals in general, and reptiles in particular. Due to their diverse morphological adaptations, their keeping and breeding offers many research and educational opportunities. Some existing skink conservation projects show that, if planned and well managed, the maintenance and breeding of *ex situ* skink populations can be successful. Nevertheless, only a very small proportion of skink species is represented in zoos. They are mostly represented by few individuals and are rarely bred. Zoos should consider focusing their expertise on keeping more threatened skink species and to increase their capacity for crucial conservation projects. Holdings of single individuals should be brought together into reproductive groups in cooperation with other institutions. Together with local institutions and stations, conservation breeding programmes should be developed or expanded for threatened species, so that the *ex situ* populations can ultimately act as a support and backup for *in situ* populations. Zoos can thus play a key role in the conservation of skink species following the IUCN's One Plan Approach by using their expertise, capacity, and financial resources to develop and implement measures to contribute to the conservation of species both *in* and *ex situ*.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2021.e01800.

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