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Agamidae in zoos: assessment of the threat status worldwide and their distribution patterns in zoological collections

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Abstract. Due to climate change and the intensifying anthropogenic impacts on ecosystems, there has been a significant decline in biodiversity. To prevent the extinction of species, in situ and ex situ conservation methods and combining different expertise are imperative according to the IUCN's One Plan Approach. To improve the conservation of threatened lizard species of the family Agamidae, this study provides a comprehensive assessment of their risk status and an evaluation of current ex situ efforts. Herein, we analysed data available through the Zoological Management Information System (ZIMS) created by Species360 and "Zootierliste" (zoo animal list) to evaluate data about the species held, the number and distribution of institutions keeping Agamidae species, and the breeding successes in these institutions. Our results show that only seven species being classified as threatened on the IUCN Red List were kept in zoological institutions using ZIMS, which amounts for ~1% of all identified agamids and ~12% of the 60 agamid species currently assessed as threatened. Species assessed as not threatened clearly dominated in terms of species diversity, number of individuals kept and breeding success in ZIMS institutions. The vast majority of species being kept was between two to ten individuals. Europe accounted for ~53% of all individuals represented in zoological collections. In order to increase the number of conservation breeding attempts supporting the One Plan Approach conservation measures, a positive shift towards keeping threatened Agamidae species in zoos should be achieved by combining tailored ex situ and in situ conservation programs to join forces.

Key words. Squamata, conservation breeding, ex situ populations, One Plan Approach, Sauria, ZIMS, zoos.

Introduction

The Agamidae is a morphologically and ecologically diverse family of lizards with an approximate number of more than 580 described species (Uetz et al. 2023) comprising the subfamilies Agaminae, Amphibolurinae, Draconinae, Hydrosaurinae, Leiolepidinae, and Uromastycinae (Liu et al. 2019, Uetz et al. 2023). Due to their wide distribution across Africa, Europe, Asia and Australia (Kissling et al. 2016), inhabiting tropical and subtropical regions (Ananjeva 2009), their ecology, morphology, and adaptation strategies vary within the family (Kissling et al. 2016).

However, climate change, the intensifying negative anthropogenic impacts on ecosystems and the associated habitat loss contribute to the increase of species listed as threatened (IUCN 2019). Terrestrial reptiles are still the least evaluated group of terrestrial vertebrates with 13% of unassessed species out of 11,733 evaluated reptile species (IUCN 2022). Currently, more than one out of five reptile species are threatened with extinction, representing 21% (Natureserve 2022) with an increasing tendency of declining population trends (IUCN 2022). Between 1970 and 2012, approximately 55% of the global population of reptiles has declined (Saha et al. 2018), which reflects the continuing risk of biodiversity loss and underlines the importance of conservation projects. Nature Serve's Global Reptile Assessment, an ongoing project concentrating on population trends, abundance and threats to reptile populations (Natureserve 2023), has published the first comprehensive assessment of reptile extinction risk status (Cox et al. 2022).

As very few studies have been published focusing on the threat status and ex situ efforts of Agamidae in general, a

comprehensive analysis of the current global threat status of Agamidae and their distributions in zoological collections seems reasonable. Nevertheless, the extinction risk of 496 Agamidae species has been assessed by the IUCN (2022). A total of 11.5% of Agamidae species have been categorized as 'Data Deficient', 76% as 'Not Threatened' and a total of 12.4% as 'Threatened'. Although species threatened with extinction should primarily be preserved through protecting their native habitat, ex situ measurements have become indispensable due to the intensifying impacts on natural habitats (Kasso & Balakrishnan 2013). The establishment and husbandry of insurance populations through ex situ breeding programs, following IUCN´s One Plan Approach, are particularly important in immediate threat situations threatening the survival of species in nature (e.g., Wahle et al. 2021, Ginal et al. 2023, Rech et al. 2023, Stenger et al. 2023). In situations such as environmental disasters, dangers caused by invasive, neozoic species, political unrest or sudden outbreak of disease, endangered species rely on the capacity, resources, and expertise of zoos. Additionally, along with reintroduction programs, zoos can contribute to the reestablishment of threatened species, once stable habitats have been ensured by in situ conservation (e.g., Wahle et al. 2021, Krizkowski et al. 2022, Ginal et al. 2023, Rech et al. 2023). Progressively more zoos support conservation projects financially or participate in establishing their own conservation projects (Tribe & Booth 2003, Keulartz 2015, Ziegler 2023). Annually, the World Association of Zoos and Aquariums (WAZA), including those institutions affiliated with national and regional associations that are not WAZA members, spend approximately US$350 million on nature conservation (Gusset & Dick 2011). With around 700 million people visiting zoos and aquariums annually (Gusset & Dick 2011), zoos provide a great platform for public outreach. This enables them to convey information about threatened species and conservation projects, encouraging visitors to donate for conservation (Miranda et al. 2023). Furthermore, zoo research enhances current knowledge of the natural history of species, potentially leading to better adapted and more successful conservation projects (Miranda et al. 2023). An increasing number of zoos are pursuing the concept of the One Plan Approach (OPA) (Miranda et al. 2023). This approach was drafted by the IUCN Species Survival Commission (SSC) and the Conservation Planning Specialist Group (CPSG) (CPSG 2023) and aims towards the protection of threatened species by connecting different stakeholders and therefore facilitating the exchange of information, resources and the division of labour to increase the effectiveness of species conservation worldwide (CPSG 2020). The CPSG has managed to successfully develop more than 500 conservation projects across a wide range of taxa over the last 40 years (CPSG 2020, Byers et al. 2022). The priorities for the selection of species in need of conservation projects are based on their extinction risk assessment, information available on the species, the threats species face in regard of conservation recovery, and the potential probability to overcome those threats (CPSG 2023). A recent study, that evaluated the impact of conservation planning, compared the pre- and post-planning interventions of 35 conservation plans from 23 countries over 13 years. The study revealed that although declines in threatened species continued after planning, the rate of decline gradually slowed, eventually resulting in a recovery trend within 15 years (Lees et al. 2021).

Since the evaluation of extinction risks is one important factor for the priority of conservation projects, and knowledge of the distribution of threatened Agamidae species in zoological collections is insufficient, this study aims to enlighten the current knowledge gaps to establish and improve tailored ex situ husbandries aligning with the concept of the One Plan Approach. Therefore, the data available in the Species360 Zoological Information Management System (ZIMS) and "Zootierliste" (zoo animal list) was analysed and evaluated to obtain an overview of the distribution of threatened and non-threatened Agamidae species in zoological collections, as well as the number of individuals and breeding successes across institutions.

Material and methods

Species data list and threat status

To establish a list with all described and currently recognized Agamidae species along with genera and subfamilies, the Reptile Database was used (Uetz et al. 2023). In addition, the IUCN Red List (IUCN 2022) was consulted to complete the list and to add additional information on threat status. For this study, the different extinction risk categories defined by the IUCN Standards and Petitions Committee (2022) were summarized in three different groups: The first group, 'No Data', included species assessed as 'Data Deficient (DD)' and 'Not Evaluated (NE)'. Species listed as 'Least Concern (LC)' or 'Near Threatened (NT)' were grouped together as 'Not Threatened'. The species fulfilling the IUCN Red List criteria and classified as 'Vulnerable (VU)', 'Endangered (EN)', or 'Critically Endangered (CR)' were comprised in the group named 'Threatened'. The categories 'Extinct in the Wild (EW)' and 'Extinct (EX)' were omitted from this analysis, since no Agamidae species appeared in one of those categories, according to the IUCN (2022) Red List. All data provided by those databases were analysed and consulted up to and including 23 August 2023.

Species holdings in zoos

The compiled species list was synchronized with the dataset of the Species360 Zoological Information Management System (ZIMS 2023), which is an online database, allowing zoos worldwide to add and share data on their animals including husbandry and medical information in order to manage populations effectively and to contribute data to global conservation initiatives. ZIMS is used by more than 1,300 aquariums, zoos, wildlife sanctuaries, and research

institutions worldwide (ZIMS 2023); e.g., more than 400 institution members of the European Association of Zoos and Aquariums (EAZA) use ZIMS to enter their holdings in order to establish, coordinate and manage tailored EAZA ex situ programs (EEPs). However, since participation in ZIMS is not mandatory for non-EAZA and WAZA members, the dataset might be incomplete. Furthermore, the study only reflects a snapshot, as the entries change frequently.

This study focused on data providing information on species numbers and the number of individuals kept in zoos, the distribution of Agamidae holdings per regions and the breeding success as measured by the number of offspring between 23 August 2022 and 23 August 2023. Only current holdings were considered, obsolete holdings being omitted. In order to obtain a detailed overview of current holdings, a second database, the so called 'Zootierliste (ZTL)' (zoo animal list) (Graf et al. 2023) was consulted. The ZTL is a database collecting data about current and obsolete holdings worldwide, allowing registered members to edit and update holdings. The database does not provide any information on the number of kept individuals nor the breeding success of holdings but only contains information on the corresponding institutions and their respective number of holdings. Further analyses were only based on the data collected from ZIMS.

Adjustments to the species data list and analysis methods

Prior to the analysis of the collected data, species registered in the established species list were checked for outdated taxonomy and were updated if necessary, using Uetz et al. (2023). For cases in which populations kept were recorded in ZIMS for both outdated and the new taxonomy, holdings were summed up and summarized under the new taxonomy. The analysis was conducted at species level. Individuals that were only listed at genus level and not allocated to a species in ZIMS were omitted from this study, because they could not be assigned a risk status according to the IUCN (2022). Following Uetz et al. (2023), we considered the following taxa that were listed as species on the IUCN (2022) Red List or in ZIMS (2023), as subspecies: *Amphibolurus minimus* (= *Pogona minor minima*), *Gonocephalus abbotti* (= *Gonocephalus doriae abbotti*), *Phrynocephalus alpherakii* (= *Phrynocephalus guttatus alpherakii*), *P. melanurus* (= *Phrynocephalus guttatus melanurus*), *P. moltschanovi* (= *Phrynocephalus guttatus moltschanowi*), *P. sogdianus* (= *Phrynocephalus interscapularis sogdianus*), *Uromastyx leptieni* (= *Uromastyx aegyptia leptieni*), *U. microlepis* (= *U. aegyptia microlepis*), *U. flavifasciata* (= *U. dispar flavifasciata*), *U. maliensis* (= *U. dispar maliensis*), and *U. philbyi* (= *U. ornata philbyi*). Four species were documented in ZIMS but not listed and assessed by the IUCN Red List, so were classified as 'Not Evaluated (NE)' in the analysis, including: *Acanthosaura murphyi, Hydrosaurus celebensis, H. microlophus,* and *Uromastyx nigriventris*. To visualize the collected data, R studios Version R 4.4.1 was used using the packages base, datasets, graphics, grDevices, methods, readxl, stats, and utils (R Core Team 2021, 2023). The association between traits among not threatened and threatened species was assessed using Monte Carlo simulations with 99% confidence intervals and 10,000 random samples. To illustrate the distribution of zoos keeping Agamidae species per region, all zoo coordinates that were provided by ZIMS were adapted by ZIMS (2023) (Fig. 3). To visualize the species richness patterns of zoos worldwide holding Agamidae species (Fig. 4), range polygons were obtained from the IUCN (2022) Red List. Species not assessed by the IUCN (2022), for which polygons were not available, have been excluded. Furthermore, the Shannon index, a measure of biodiversity, was calculated by considering the number of unique species and the density of individuals per species. To map the species richness in zoos according to their respective origin (Africa, Asia, Europe, Oceania) the Geographical Information System (QGIS) (QGIS Development Team 2023) was used. European, North American, and Asian zoos kept Agamidae species from all regions of origin, including Africa, Europe, Asia, and Australia (Fig. 4). In the following analysis, all numerical values were rounded.

Results

Risk status

In total 578 species were assessed in seven IUCN Red List categories worldwide (Fig. 1A) of which 77 species were kept in zoological collections according to ZIMS (2023) (Fig. 1B). Among the 77 species kept in zoos a total of 83.1% were assessed as 'Not Threatened' (77.9% 'Least Concern (LC)', 5.2% 'Near Threatened (NT)'), 9.1% were evaluated as 'Threatened' (6.5% 'Vulnerable (VU)', 2.6% 'Endangered (EN)'), and 7.8% were assessed as 'No Data' (6.5% 'Not Evaluated (NE)', 1.3% 'Data Deficient (DD)'). No species was assessed as 'Critically Endangered (CR)'. Out of all 578 identified species, 60 Agamidae species (10.4%) were assessed as 'Threatened'; however, only seven of these (~12%) were represented in zoological collections (Table 1). This indicates that just five out of 27 species assessed as 'Vulnerable (VU)', two out of 23 species evaluated as 'Endangered (EN)', and none out of ten species assessed as 'Critically Endangered (CR)' are currently represented in zoos according to ZIMS.

Total number of individuals per species represented in ZIMS Institutions

Of the seven threatened Agamidae species kept in zoological collections, one species was represented by only a single individual (14.3%), one species by two to ten individuals (14.3%), and one species by 11 to 50 individuals (14.3%). Two threatened species were kept with 51 to 100 individuals (28.6%), while another two species were kept with popula-

Table 1. Representation of all species assessed as 'Threatened' (n = 60) (VU = Vulnerable, EN = Endangered) and kept in zoological institutions (n = 7) according to ZIMS, along with the population trend (Pop. trend) (–: stable, ↓: decreasing, ?: unknown), the number of individuals kept according to their sex, (M: Male, F: Female, O: Other (unknown sex)) the total number of bred (offspring), the number of institutions (Inst.) keeping Agamidae species, and the region (Af = Africa, As = Asia, Eu = Europe, Na = North America, Sa = South America, Oc = Oceania) in which the institutions are located.

Subfamily/Species	Risk status	Pop. trend	Individuals (M/F/O)	Offspring	Inst.	Region of institutions
Agaminae						
Trapelus savignii	VU	↓	1(0/0/1)	0	1	Eu
Amphibolurinae						
Physignathus cocincinus	VU	↓	379(45/74/260)	70	76	As, Eu, Na
Tympanocryptis pinguicolla	EN	↓	19(12/7/0)	60	2	Oc
Hydrosaurinae						
Hydrosaurus weberi	VU	↓	65(14/22/29)	7	26	As, Eu, Na
Leiolepidinae						
Leiolepis guentherpetersi	EN	↓	2(0/2/0)	0	1	Eu
Uromastycinae						
Uromastyx aegyptia	VU	↓	59(9/10/40)	0	58	Af, As, Eu, Na, Eu
Uromastyx thomasi	VU	↓	11(6/1/4)	0	5	
Agaminae						
Agama montana	VU	?				
Ctenophorus nguyarna	VU	?				
Phrynocephalus golubewii	CR	↓				
Phrynocephalus horvathi	CR	↓				
Phrynocephalus persicus	VU	–				
Phrynocephalus rossikowi	EN	↓				
Phrynocephalus saidalievi	VU	↓				
Phrynocephalus strauchi	VU	↓				
Amphibolurinae						
Diporiphora vescus	VU	?				
Tympanocryptis condaminensis	EN	↓				
Tympanocryptis wilsoni	EN	?				
Draconinae						
Acanthosaura titiwangsaensis	EN	?				
Bronchocela vietnamensis	VU	?				
Calotes desilvai	CR	?				
Calotes liocephalus	EN	↓				
Calotes manamendrai	EN	?				
Calotes nigrilabris	EN	↓				
Calotes paulus	EN	?				
Calotes pethiyagodai	EN	?				
Ceratophora aspera	EN	?				
Ceratophora erdeleni	CR	↓				
Ceratophora karu	CR	?				
Ceratophora stoddartii	EN	?				
Ceratophora tennentii	EN	↓				
Cophotis ceylanica	EN	?				
Cophotis dumbara	CR	?				
Coryphophylax brevicauda	VU	?				
Diploderma brevipes	VU	↓				
Diploderma luei	EN	↓				
Diploderma makii	VU	↓				

Table 1 continued

Subfamily/Species	Risk status	Pop. trend	Individuals (M/F/O)	Offspring	Inst.	Region of institutions
Gonocephalus kuhlii	VU	?				
Harpesaurus modiglianii	EN	?				
Japalura dasi	VU	?				
Lyriocephalus scutatus	VU	?				
Microauris aurantolabium	EN	?				
Monilesaurus acanthocephalus	EN	?				
Otocryptis beddomii	EN	—				
Pseudocalotes andamanensis	VU	↓				
Pseudocalotes flavigula	CR	—				
Pseudocalotes floweri	VU	?				
Pseudocalotes larutensis	VU	—				
Pseudocalotes poilani	EN	↓				
Pseudocalotes rhaegal	CR	?				
Pseudocalotes viserion	VU	—				
Sarada superba	CR	—				
Sitana devakai	VU					
Sitana fusca	CR	↓				
Sitana marudhamneydhal	EN	↓				
Sitana schleichi	EN	?				
Sitana visiri	VU	?				
Leiolepidinae						
Leiolepis boehmei	VU	↓				
Leiolepis ngovantrii	VU	?				
Uromastycinae						
Saara hardwickii	VU	↓				

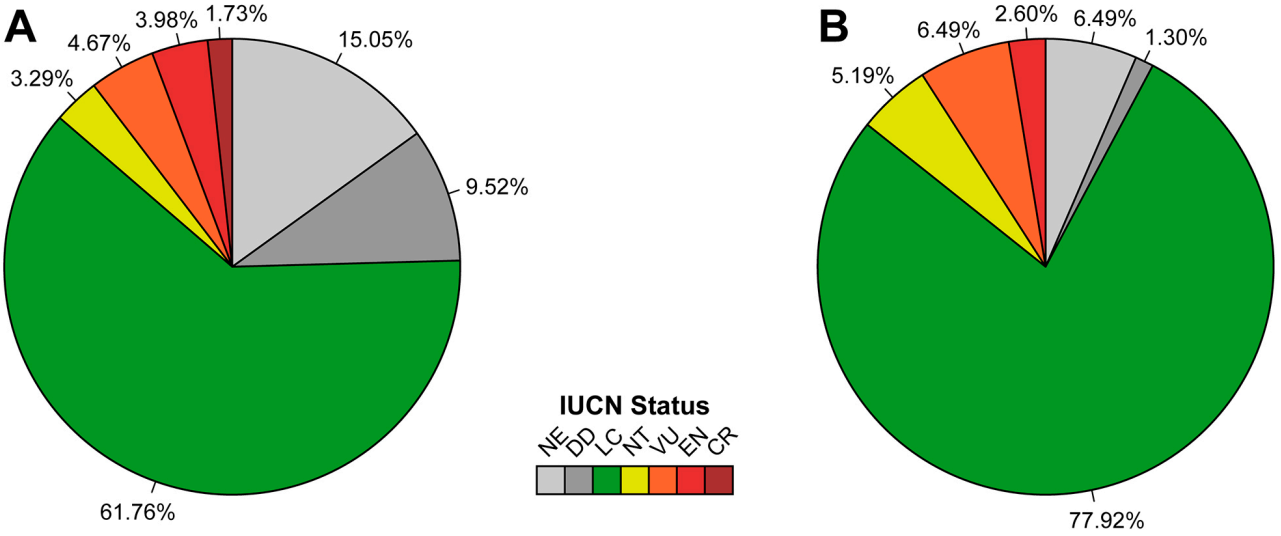

Figure 1. Distribution of risk status among Agamidae species. (A) All identified species worldwide (n = 578) and (B) in zoos (n = 77) according to ZIMS (2023). IUCN categories: NE = Not Evaluated, DD = Data Deficient, LC = Least Concern, NT = Near Threatened, VU = Vulnerable, EN = Endangered, CR = Critically Endangered. Since no species were assessed as 'Extinct in the Wild (EW)', and 'Extinct (EX)' those categories were omitted.

tions exceeding 100 individuals (28.6%) (Fig. 2A). The distribution of individuals across ZIMS institutions partially deviates from the results expected by chance [$p < 0.01$, 99%, CIs: single individual 15.2%–15.9%, 2–10 individuals 38.5%–39.4%, 11–50 individuals 21.7%–22.5%, 51–100 individuals 11.3%–11.9%, > 100 individuals 11.5%–12.1%].

Breeding success

Between 23 August 2022 and 23 August 2023, a total of 19 species was successfully bred within zoological collections, of which 15 species were assessed as 'Not Threatened' (78.9%) (Table 2, Fig. 2B). In contrast, a total of three threatened species were successfully bred (15.8%), resulting in a higher percentage as expected from a random selection [$p < 0.01$, 99%, CI: 8.9% – 9.4%].

Geographical distribution

With 512 institutions, Europe was the region with the majority of institutions keeping Agamidae species in their collections, representing 52.9% (512 out of 968) (Fig. 3). It also exhibited the greatest species density and diversity. In terms of species diversity, six Agamidae species assessed as threatened were kept in European institutions. North American zoos followed in terms of the number of individuals and species diversity, as well as in keeping threatened Agamidae species (3 species), similar to the situation in Asia, where three threatened Agamidae species were also kept. European zoos, however, had the greatest geographical diversity and species richness. African and Oceanian zoos mainly kept Agamidae species native to the respective region, with Oceanian zoos representing the highest species richness of all regions, with species native to Australia. Zoos located in South America mainly kept Agamidae species from north and central Oceania and represented the lowest species richness.

Discussion

Threat status

The distribution of species represented in ZIMS institutions covers only a small fraction of Agamidae species (13.3%). In comparison to similar studies, the imbalance between threatened and non-threatened Agamidae species is considerably stronger (Wahle et al. 2021, Rech et al. 2023). Only 1.2% of all Agamidae and approximately 12% of those species assessed as 'Threatened' are distributed in zoos. It is especially noticeable that none of the species assessed as 'Critically Endangered (CR)' are represented in zoological collections (*Calotes desilvai, Ceratophora erdeleni, C. karu, Cophotis dumbara, Phrynocephalus golubewii, P. horvathi, Pseudocalotes flavigula, P. rhaegal, Sarada superba, Sitana fusca*). However, in some species the IUCN status might not reflect the actual conservation status since the last assessments may be outdated: e.g., according to Melville et al. (2019), *Tympanocryptis pinguicolla* was thought to be extinct due to significant habitat destruction, however in 2023 the species was rediscovered (Australian Government

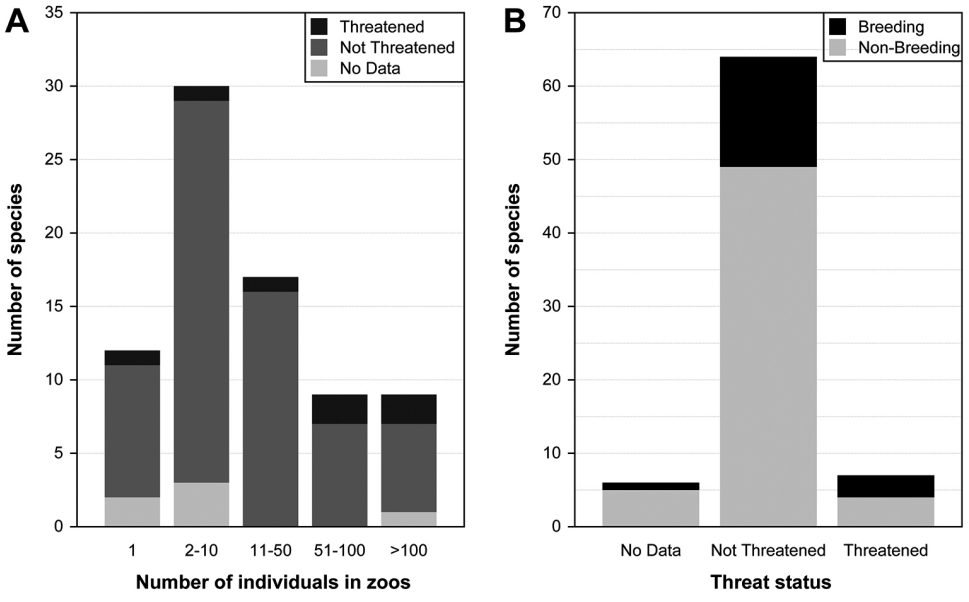

Figure 2. (A) Total number of individuals per species represented in zoological collections according to ZIMS (2023), categorized by their threat status. (B) Agamidae species with and without documented breeding success in ZIMS within the 23 August 2022 and the 23 August 2023. Black represents species which were successfully bred and grey represents species which were not bred. The number of species represents the species diversity, not the total number of holding per species. 'No Data' = Not Evaluated (NE), Data Deficient (DD); 'Not Threatened': Least Concern (LC), Near Threatened (NT); 'Threatened' = Vulnerable (VU), Endangered (EN), Critically Endangered (CR).

Table 2. Representation of the breeding success per species (n=19), along with IUCN status (NE = Not Evaluated, LC = Least Concern, VU = Vulnerable, EN = Endangered), the population trend (Pop. Trend) (–: stable, ↓: decreasing, ?: unknown), the total number of offspring bred between the 23 August 2022 and the 23 August 2023, the number of institution keeping the certain species (Inst.) and the region in which the institutions are located (Eu: Europe, Na: North America, Oc: Oceania).

Subfamily/ species	Risk status	Pop. trend	Offpring	Inst.	Region of institutions
Agaminae					
Agama agama	LC	–	14	1	Eu
Stellagama stellio	LC	–	16	1	Eu
Stellagama vulgaris	NE	?	12	2	Eu
Xenagama taylori	LC	?	7	1	Na
Amphibolurinae					
Chlamydosaurus kingii	LC	?	22	4	Eu
Ctenophorus vadnappa	LC	↓	13	2	Na, Oc
Hypsilurus magnus	LC	?	2	1	Eu
Intellagama lesueurii	LC	–	9	1	Oc
Lophosaurus boydii	LC	–	17	4	Oc
Moloch horridus	LC	–	7	1	Oc
Physignathus cocincinus	VU	↓	77	5	Eu
Pogona barbata	LC	–	7	1	Oc
Pogona vitticeps	LC	?	29	2	Eu, Na
Tympanocryptis lineata	LC	?	5	1	Oc
Tympanocryptis pinguicolla	EN	↓	71	1	Oc
Draconinae					
Acanthosaura nataliae	LC	?	6	1	Eu
Hydrosaurinae					
Hydrosaurus pustulatus	LC	↓	8	1	Eu
Hydrosaurus weberi	VU	↓	7	2	Eu, Na
Uromastycinae					
Uromastyx ocellata	LC	↓	2	1	Eu

2023a). A revision of the conservation status of this species is imperative, as it is currently classified as Endangered by the IUCN, but has already been classified as Critically Endangered by the Flora and Fauna Guarantee Act in 1988 Threatened List (Victoria State Governement 2023).

As described in previous studies, several zoos are still prioritizing charismatic species instead of collecting information on species in need of conservation (Miranda et al. 2023). The management of threatened species can be challenging due to the limited available knowledge of husbandry and general ecology requirements (Feliciano et al. 2023). Therefore, the European Association of Zoos and Aquariums (EAZA) and the World Association of Zoos and Aquariums (WAZA) are helping in regards of establishing and coordinating in- and ex situ conservation plans for zoos and aquariums following the concept of the One Plan Approach (Barongi et al. 2015, EAZA 2023). In total, both associations have more than 800 members, all demonstrating a commitment to conservation. Each member engages in different ways, such as educating and engaging with the public, conducting research, providing insurance population for vulnerable species through ex situ projects, supporting in situ projects and establishing long term conservation management plans (Barongi et al. 2015, EAZA 2023). In general space and resources are limited, therefore species selection should be well-planned. Thus, the Taxon Advisory Groups (TAGs) identify taxa for inclusion in the EAZA Ex Situ Programs (EEPs) as part of the Regional Collection Plan (RCP). This process improves, enhances, specifies, and adjusts the guidelines of suitable conservation plans (EAZA 2023). Several new EEPs for threatened lizard taxa, among them agamids, were proposed during the most recent assessment for the RCP for lizards in 2023.

Representation of individuals

Considering the total number of individuals of an agamid species across all institutions, over one-third of these holdings generally consist of between two to ten individuals.

However, according to Witzenberger & Hochkirch (2011) to avoid inbreeding and the loss of genetic diversity a minimum size of 15 founders and a population size of minimum 100 individuals should be kept in order to achieve sustainable breeding success. If the population sizes consist of fewer than 100 individuals and the species are threatened with extinction, it becomes challenging to preserve 90% of the genetic variability (Keulartz 2015). Based on the available data, no conclusions can be drawn about population founders, as information on founder individuals in ZIMS maintained populations was not available. A total of 11.7% of all kept species in zoos were held by 100 or more individuals, including two species assessed as threatened (*Physignathus cocincinus*, *Tympanocryptis pinguicolla*).

Breeding success

Overall, 24.7% of the agamid species currently kept in zoos were successfully reproduced between the 23 August 2022 and 23 August 2023. Of the seven Agamidae species assessed as threatened, a total of three species were successfully bred. The highest breeding success within one institution was achieved by the Melbourne Zoo in Australia in cooperation with the conservation organization Zoos Victoria (Zoos Victoria 2023). Between the above-mentioned timeframe, the Melbourne Zoo successfully bred 60 offspring of the native and endangered species *Tympanocryptis pinguicolla,* the former subspecies of *T. lineata*, despite challenges such as territoriality and female selectiveness in partner choice (Australian Capital Territory Government 2023). Another conservation initiative focusing on *T. pinguicolla* is the Tidbinbilla Nature Reserve, which opened in 2021. Within its first ten months, the reserve successfully bred 30 offspring (Australian Capital Territory Government 2023). Besides ex situ breeding efforts, in situ measurements are being undertaken to reintroduce the species back into the wild. However, due to limited knowledge of potential threats and insufficient progress in habitat restoration, the reintroduction into the natural environment has

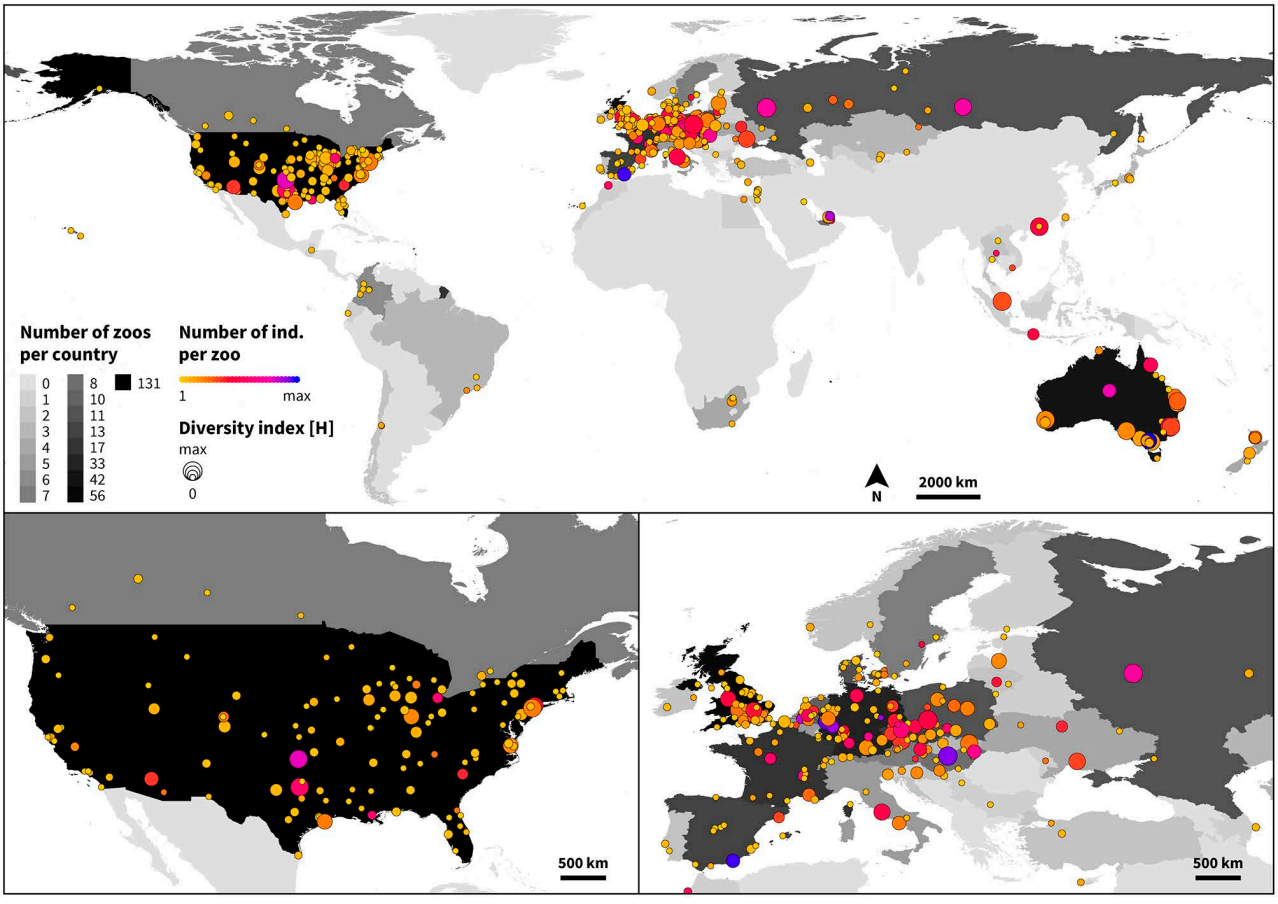

Figure 3. Visualization of the distribution of zoos keeping Agamidae species per region, the total number of individuals per institution and the species diversity per institution. The total number of zoos per country is represented by different shades of grey, light grey represents a distribution of one zoo per country, whereas black represents a total of 131 zoos per country. The colours within the circles represent the number of individuals per institution. The colour gradient transitions from yellow, through orange, red, pink and purple to blue. Yellow represents one individual and blue more than 100 individuals per institution. The radius of the coloured circle represents the diversity of species kept in the institutions. The larger the circle the more species are represented within one institution.

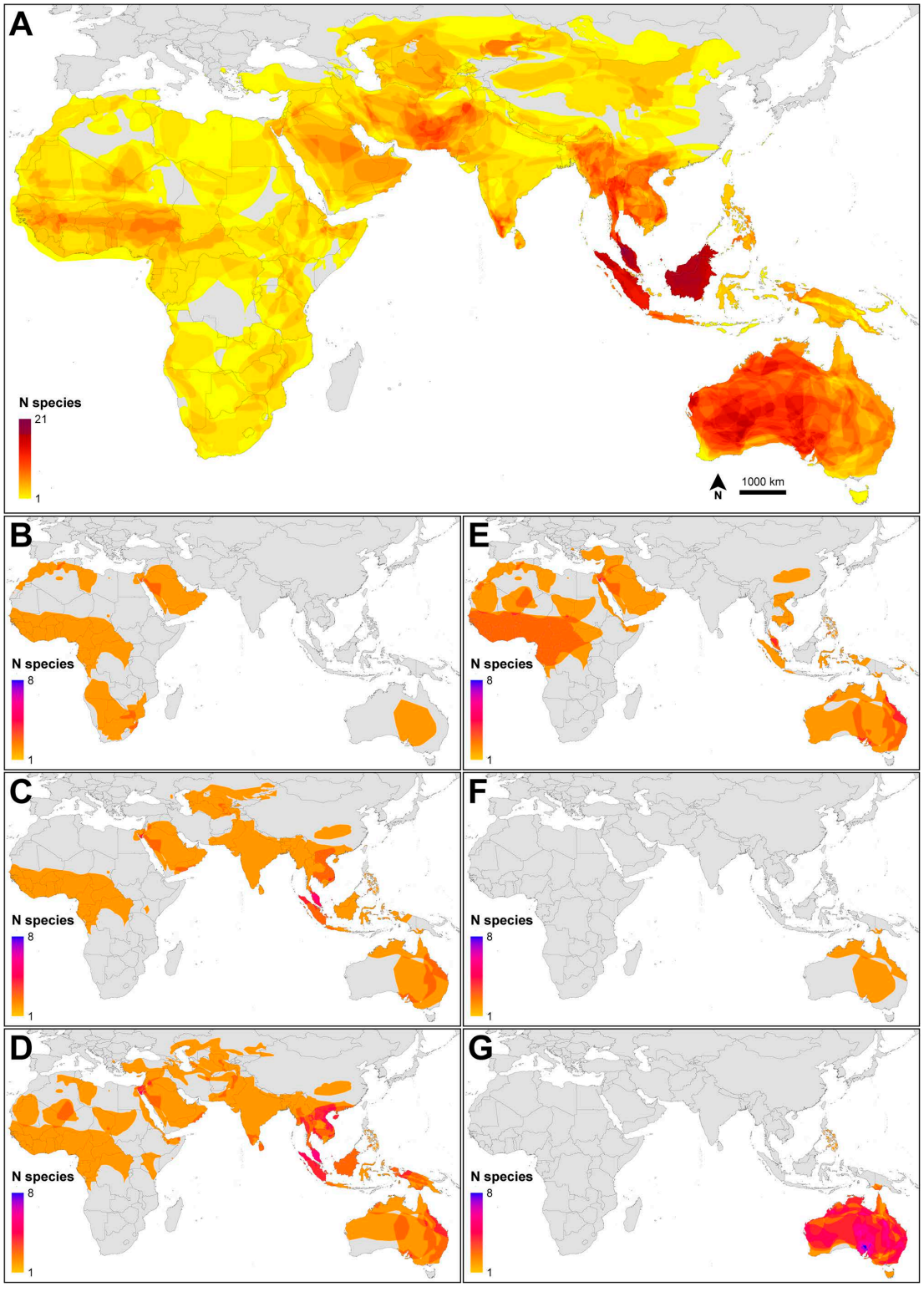

Figure 4. Geographical representation of the distribution of Agamidae species kept in European, North American, Asian, African, Oceanic and South American zoos according to their region of origin. A: Overall richness, B: African zoos, C: Asian zoos, D: European zoos, E: North American zoos, F: South American zoos, G: Oceanian zoos. In Figure 4A a colour gradient from yellow, through orange and red to brown visualizes the species richness. Yellow represented zero species, while brown illustrates the highest species richness of 21 species. In contrast, the colour gradient in Figures 4B – 4G is represented by the colours yellow, red, purple and blue, whereas yellow indicates the lowest and blue the highest species richness.

not yet been achieved (Australian Capital Territory Government 2023). Furthermore, a total of 70 offspring of the species *Physignathus cocincinus* are documented in ZIMS institutions. However, these breeding successes occurred across multiple institutions. Notably, this species is among the few threatened species with a sufficient number of individuals to support breeding programs. Close cooperation between different zoological institutions and the exchange of individuals could lead to the successful establishment of breeding programs and therefore insurance populations. To further enhance breeding success, determination of the sex of unsexed individuals is recommended. In 2021 the Cologne Zoo, successfully bred a female of *Leiolepis guentherpetersi*, which, alongside with *Tympanocryptis pinguicolla*, is the only species assessed as 'Endangered (EN)' that is both represented and successfully bred in zoological collections. Another *Leiolepis* species that is not yet listed in an IUCN Red List threat category but has the potential to be classified as threatened in the future due to heavy trade for human consumption is *L. guttata*. Currently, the species is listed as 'Data Deficient (DD)' on the IUCN Red List, but with declining natural populations. As a proactive measure, and in agreement with the authorities, Cologne Zoo initiated a breeding attempt, achieving its first breeding successes recently. Furthermore, a breeding assessment of three endangered Sri Lankan Agamidae species was published in 2020. According to the UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) (2020) all three species (*Ceratophora stoddarti, C. aspera, Lyriocephalus scutatus*) are feasible for breeding in human hands by experienced breeders. However, none of these species are currently kept in any ZIMS institutions.

Regional distribution

Europe maintained the greatest species diversity and the highest number of individuals among Agamidae species kept. However, considering the species diversity, only 12.8% of the species kept were assessed as 'Threatened' and kept in European zoos. The large number of zoos spread throughout Europe and North America (ZIMS 2022), combined with their resources and expertise, could support the maintenance of more threatened species in adequate individual numbers. ZIMS institutions worldwide primarily focus on keeping Agamidae species from Australia, with Oceanian zoos prioritizing native species, resulting in the highest species richness in the region (Midtgaard 2022). As mentioned above, two conservation projects located in Australia are concentrating on ex- and in situ conservation measures for the native and endangered species *Tympanocryptis pinguicolla* (Australian Capital Territory Government 2023, Zoos Victoria 2023). In addition, several research projects aim to address knowledge gaps related to the distribution, population abundance, habitat characteristics of, and key threats to Agamidae species native to Asia. The collection of data is essential for establishing a foundation for long term monitoring and the development of tailored conservation strategies (The Rufford Foundation 2022, SOS IUCN 2023). While the primary focus should be on preserving species threatened with extinction through in situ conservation, ex situ conservation has become indispensable due to the intensifying habitat destruction caused by anthropogenic activities and climate change. Although ex situ conservation within a species' region of origin facilitates potential reintroduction into its native habitat, ex situ conservation outside the region of origin plays a crucial role. In cases of immediate threat such as disease outbreaks, natural catastrophes, or political unrest, safeguard populations located in multiple institutions and regions increase the success of conservation measures and survival rate (e.g., Wahle et al. 2021).

Recommendations and outlook

As the results have shown, approximately 10% (60 species) of Agamidae species are threatened with extinction. Currently, 77 Agamidae species are held by zoos. A shift towards keeping threatened species would optimize the use of valuable zoo resources and spaces, leading to more effective conservation outcomes following the concept of the One Plan Approach. To establish tailored ex situ conservation and ensure the preservation of threatened Agamidae species, a shift towards prioritizing the keeping of threatened species in zoological collections is recommended. Zoo resources and space should especially be assigned to the species assessed as threatened (e.g., *Hydrosaurus weberi, Physignathus cocincinus, Tympanocryptis pinguicolla, Uromastyx aegyptia, U. thomasi*) and already kept in ZIMS institutions. To establish stable reserve populations of endangered species through ex situ breeding, a minimum of 100 individuals per species is required to maintain long-term conservation. Currently, the majority of threatened species are not yet kept in suitable numbers for breeding programs, as genetic diversity is limited due to small populations and fragmented distribution across institutions. However, the breeding success and extensive distribution of *Physignathus cocincinus* and *Hydrosaurus weberi* across more than 50 institutions is a convincing example of effective ex situ conservation efforts. The exchange of suitable individuals within institutions located in several regions is strongly recommended to establish successful breeding programs and safeguard populations. Therefore, cooperation and communication between zoological institutions across regions is of great importance. Given the limited number of facilities per species in zoos, cooperation with programs like Citizen Conservation (https://citizen-conservation.org/en/) could also be an option to extend the conservation breeding network and to reach the required numbers of individuals for maintaining healthy ex situ populations.

However, the exchange in particular between threatened species across regions poses special challenges. The Convention on International Trade in Endangered Species

(CITES 2023) protects endangered species from exploitation and further population decline through export by imposing strict conditions. The threatened Agamidae species listed under the CITES appendices are subjected to severe regulations and mostly originate from Sri Lanka and Australia (Australian Government 2023b, CITES 2023). Therefore, the acquisition of these endangered species for ex situ conservation and breeding programs can be complicated and imposes legally challenging processes.

Nevertheless, it is strongly recommended that the export of wild-caught individuals be avoided, as it could increase the illegal wildlife trade and contribute to population declines in the wild. The import of wild-caught Agamidae individuals also is particularly problematic, as they are often in a very bad condition upon arrival. Zoos should focus on acquiring species that are already held in zoological collections. Another option is to assist authorities in housing confiscated individuals. Such administrative support helps the authorities, ensures the rescue of animals and simultaneously provides a chance to establish a conservation breeding program, following specific identification and genetic screening to determine their allocation to a particular geographical lineage. In any case, ex situ measures should be ideally combined with in situ measures in the country of origin in the sense of the One Plan Approach. Therefore, partnerships with conservation organisations and authorities in the country of origin are of great importance. An effective strategy is the development of local conservation efforts to establish legal and sustainable breeding stations within the species' region of origin. The collaboration between those local conservation sanctuaries and international zoological collections can overcome regulatory challenges. By breeding species locally and gathering extensive knowledge of their ecology and husbandry, the export of species to international institutions can be subsequently considered as a way of extending the conservation breeding network. This approach also ensures the alignment between breeding programs and national conservation and recovery plans. Several zoos are already designing tailored Regional Collection Plans, focusing on the establishment of conservation and breeding programs within the region of origin of species. As demonstrated by the cooperation between the Tidbinbilla Nature Reserve and the Melbourne Zoo in Australia, local conservation projects can effectively achieve breeding success contributing to the establishment of insurance populations and long-term conservation. Once the necessary habitat requirements are effectively implemented, species can be reintroduced into their natural habitat.

Furthermore, local conservation sanctuaries could help address the challenge of acquiring threatened species that are not yet represented in zoological collections. Local conservation stations could collaborate closely with local authorities to integrate selected wild-caught individuals into conservation breeding programs, such as implemented by the Tidbinbilla Nature Reserve for the species *Tympanocryptis pinguicolla*.

Thus, zoos pursuing the One Plan Approach play a crucial role in the conservation of threatened species. This is also reflected by the recent inclusion of data on ex situ holdings from ZIMS in the IUCN Red List, emphasizing the importance of aligning conservation efforts both in situ and ex situ. Through the collaboration among different stakeholders, including zoological institutions across different regions, zoo associations like WAZA and EAZA, conservation organisations and local conservation sanctuaries and governments, the establishment of reserve populations and coordinated breeding programs becomes achievable. A shift towards keeping threatened species and the integration of tailored ex situ and in situ efforts would optimize the use of valuable zoo resources and spaces, leading to more effective conservation outcomes supporting the One Plan Approach. Equipped with resources and knowledge, zoos can play an important role especially in ex situ conservation. This allows zoos to establish, as conservation zoos, sanctuaries in the sense of modern arks (Ziegler 2023) to prevent the extinction of threatened populations through breeding programs and implement reintroduction programs aiming towards the reestablishment of endangered species in stable habitats ensured by in situ conservation.

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