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Biases in the current knowledge of threat status in lizards, and bridging the 'assessment gap'

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ABSTRACT

Reptiles represent the world's most diverse group of terrestrial vertebrates (~10,300 recognized species). Knowledge of their conservation status, however, lags behind that of birds, mammals and amphibians. Only ~40% of the world's reptile species have had their conservation status assessed by the IUCN, and detailed analysis of extinction risk has been limited to a subset of 1500 species. Using lizards (Sauria and Amphisbaenia), the most diverse group of reptiles, we investigated whether biases in distribution, ecology, life-history and taxonomy exist in the species that have been assessed to date by the IUCN. Our results highlight that only 36% of the ~6300 described lizard species have had their conservation status assessed. Whilst data deficiency is a key concern in lizards (16% of assessed species), the large number of non-assessed species (~4000 species) represents a larger and more pressing issue. Accentuating this 'assessment gap' is the fact that biases exist in the subset of lizard species that have been assessed by the IUCN. Australia and Asia, as well as tropical areas in general, were the least assessed regions. Assessed lizard species were more likely to have larger body and clutch sizes, broader distributional and elevational ranges, occur at more northerly latitudes, and have a viviparous mode of reproduction. Some evidence suggests that they also tend to be diurnal, surface active, and with developed limbs. The level of assessment also differed significantly among lizard families and higher taxa. We recommend the implementation of an integrated approach to bridge the 'assessment gap' in lizards, involving regional and taxon-specific working groups associated with the IUCN's Global Reptile Assessment, predictive modelling, enhanced knowledge of lizard distribution and biology, and improved taxonomic methods.

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1. Introduction

Human activities have led to the documented loss (extinct, extinct in the wild, possibly extinct) of ~620 vertebrate species over the last 500 years, marking the onset of a sixth mass extinction event (Ceballos et al., 2015). The key threatening processes for terrestrial vertebrates are habitat loss and degradation, overexploitation, invasive species, and climate change (Thomas et al., 2004; Sinervo et al., 2010; Hoffmann et al., 2010; Foden et al., 2013; Böhm et al., 2016–in this issue), with most species impacted by multiple threat processes (Cardillo et al., 2005; Böhm et al., 2013). Whilst the drivers of species extinction risk have been extensively investigated over the last two decades in mammals (e.g., Cardillo et al., 2005; Fritz et al., 2009; Davidson et al., 2012; Di Marco et al., 2012), birds (e.g., Bennett and Owens, 1997; Owens and Bennett, 2000; Lee and Jetz, 2011), and amphibians (Stuart et al., 2004; Wake and Vrendenburg, 2008; Sodhi et al., 2008; Cooper et al., 2008; Howard and Bickford, 2014), the first global analysis of the conservation status of reptiles was completed relatively recently (Böhm et al., 2013). To further exemplify the extent to which our understanding of

extinction risk in reptiles lags behind other terrestrial vertebrate groups, Böhm et al.'s (2013) analysis only considered 1500 randomly selected species (just 14.6% of the 10,270 described species as of August 2015; Uetz and Hosek, 2015), and many of these (21%) were classified as 'Data Deficient' (see Bland and Böhm, 2016–in this issue).

In contrast, the IUCN has successfully completed assessing the threat status of birds (~99%, 9895 of ~9900 species; AviBase, http://avibase.bsc-eoc.org/avibase.jsp?lang=EN) and mammals (~99%, 5413 of ~5500 species; Mammal Species of the World, http://vertebrates.si.edu/msw/mswCFApp/msw/index.cfm), and the vast majority of described amphibians (6247 of ~7500 species; Amphibian species of the World Database, http://research.amnh.org/vz/herpetology/amphibia/index.php) (Hoffmann et al., 2010; IUCN, 2015).

Altogether, only ~40% of described reptile species have been assessed by the IUCN (IUCN, 2015), including those considered in Böhm et al. (2013). Furthermore, most species have been categorized based on range size (i.e. Category B criteria). Why have reptiles, the largest class of tetrapods, been neglected? Potential explanations include the lower level of research that has been conducted on reptiles (Bonnet et al., 2002), their more secretive behaviour (Doody et al., 2013), adverse public perception (Kellert, 1993), and high rates of cryptic species diversity (Oliver et al., 2009; Rosauer et al., 2016–in this issue).

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Whatever the cause, reptiles are still being discovered and described at an astronomical rate (~200 species are being added per year) (Uetz and Hosek, 2015). Thus, despite their recent efforts through the Global Reptile Assessment (GRA; http://www.iucnredlistassessments.org/the-global-reptile-assessment/), the IUCN struggles to keep up with these additions, and to update assessments that are necessitated by this taxonomic activity (e.g., splitting of existing species into several taxa). The relatively recent description of many species (>1800 in the 21st Century so far — and many more revalidations of synonyms and elevation of subspecies to species rank, Uetz and Hosek, 2015) has resulted in an incomplete knowledge of reptilian biogeography, population density, ecology and life history (Meiri, accepted for publication).

Few assessments of reptile extinction risk were completed prior to Böhm et al. (2013), and those that were focused on specific taxonomic groups (elapid snakes, Reed and Shine, 2002; lacertid lizards, Siliceo and Diaz, 2010; New Zealand lizards, Tingley et al., 2013a). However, since the publication of Böhm et al. (2013) there has been a flurry of analyses based on species assessed by the IUCN (Böhm et al., 2016–in this issue; Tomovic et al., 2015; Tolley et al., 2016–in this issue; Roll et al., 2016–in this issue; Bland and Böhm, 2016–in this issue; Tolley et al., 2016–in this issue; Maritz et al., 2016–in this issue). But how representative of the broader reptile fauna are the subset of species that have been assessed? And do distributional, ecological, life-history or taxonomic biases exist in the reptile species that have been assessed by the IUCN? The existence of biases in the assessed reptile species could potentially influence the generality of some key findings of Böhm et al. (2013), namely: i) 19% of reptile species being threatened with extinction, ii) 21% of species being Data Deficient, iii) threat status being higher in freshwater environments, tropical regions and oceanic islands, and iv) Data Deficient species occurring more frequently in tropical areas (Central Africa, South-East Asia) and among fossorial species.

Here we investigate whether biases in distribution, ecology, life-history and taxonomy exist in the lizard species that have been assessed to date by the IUCN. Lizards represent 60% of reptile diversity (6304 valid species to date of which 36% are assessed; Table 1), but have lower levels of assessment compared to snakes (51% of 3567 species assessed), turtles (67% of 341 species), crocodiles (92% of 25 species), and the tuatara (100% of 1 species) (IUCN, 2015; Uetz and Hosek, 2015). Lizards (here including the squamate suborders Sauria and Amphisbaenia) are highly diverse and nearly cosmopolitan, with a plethora of life styles, reproductive characteristics, sizes, shapes and colours- and threats (Pianka and Vitt, 2003). Knowledge of potential biases in the traits of species that have been assessed will act to inform conservation and focus efforts towards the taxa and regions that are in the greatest need of investigation and determination of their conservation status. We predicted that assessed species were more likely to occur in areas of high levels of research activity (i.e. Northern Hemisphere regions; e.g., Europe, northern North America), have wide ranges, wide elevational ranges, occur at lower elevations in temperate

biomes (that have been better studied than the tropics and desert regions), and in continental (rather than oceanic) regions. Furthermore, we predicted that species that were more obvious and easier to study (e.g., large, long-lived, viviparous, diurnal, surface active, limbed species), and have been known for longer (i.e. described earlier), would have higher rates of assessment. Due to deep phylogenetic divergences in the distribution, biology and ecology of lizard lineages and families (Vitt et al., 2003; Vitt and Pianka, 2005), we predicted any biases would manifest themselves as different levels of assessment among lizard taxonomic groupings.

2. Methods

IUCN lizard assessments were downloaded from the IUCN website (http://www.iucnredlist.org/) on the 24th June 2015. Binomials were compared to the March 2015 version of the reptile database (http://www.reptile-database.org/; downloaded on the 2nd April 2015) — we consider only species included in this dataset, or described since (surprisingly many: 41 species at the time of analyses). We updated the names in the IUCN database according to the reptile database taxonomy, but only included data where there was a one-to-one fit between a reptile database name and an IUCN one (i.e., entities considered species by the IUCN, but subspecies, or populations within larger species by the reptile database were omitted). We restricted our analyses to lizards and amphisbaenians (henceforth "lizards") because they are less well assessed than other reptile taxa. We treated data on the lizards assessed by the Institute of Zoology (IOZ; Böhm et al., 2013) in a similar manner to which we treated IUCN data. Four species included in Böhm et al. (2013): *Basiliscus vittatus*, *Gonatodes albogularis*, *Microlophus albemarlensis*, and *Sphaerodactylus argus* (all considered Least Concern by Böhm et al.) are listed as having no IUCN assessments. We treat them as assessed (and not DD) in subsequent analyses (see below). *Leiolopisma fasciolare* — a dubious species from an unknown locality and with no ecological data (not assessed by the IUCN) was omitted.

We collected data on lizard traits from the literature, and in a few cases, in the field (see Meiri, 2008; Meiri et al., 2012, 2013, 2014; Scharf et al., 2015 for details). The following categories of traits were recorded:

- Distribution: *Geographic range* data (including *range size* [log transformed] and *latitudinal centroids*) for all lizards were obtained from the GARD (Global Assessment of Reptile Distributions) working group (http://www.gardinitiative.org). A lizard was considered to inhabit the *biogeographic realm* (according to the realm definition in Wallace 1876) and *biome* (biome data obtained from the WWF, https://www.worldwildlife.org/biome-categories/terrestrial-ecoregions) where the largest part of its range resides in order to consider each species only once. An alternative approach is to consider a species as present at all the realms or biomes it inhabits (or in which a substantial part of its range is found). Given that most lizards are endemic to a single realm or biome, however (e.g., 91.2% of species inhabit just one realm, 92.6% have >90% of their distribution in one realm), such an approach is unlikely to change the results of our analysis. We grouped the "tropical and subtropical" biomes of the IUCN designation ("Tropical and subtropical moist broadleaf forests", "Tropical and subtropical dry broadleaf forests", "Tropical and subtropical coniferous forests" and "Tropical and subtropical grasslands, savannas and shrublands") into one "tropical" biome, and similarly grouped the "Temperate broadleaf and mixed forests", "Temperate Coniferous Forest", "Boreal forests/Taiga" (the latter with one species, *Zootoca vivipara*) and "Temperate grasslands, savannas and shrublands" biomes into one "Temperate" biome. We did not analyse the "Flooded grasslands and savannas" biome because too few species inhabit this biome for meaningful analyses. Species were considered *insular endemics* if they inhabit no continent (i.e., if they only inhabit landmasses smaller than Australia). *Elevation* data were directly recorded from the literature and not derived from range maps.

Table 1
Levels of lizard assessment among different realms numbers are species numbers. Percentages are from the realm totals.

Realm	Total	Non-assessed	Assessed		
			Total assessed	Assessed, not DD	Assessed, but not in Böhm et al. (2013)
Afrotropic	959	587 (61%)	372 (39%)	306 (32%)	243 (25%)
Australia	747	638 (85%)	109 (15%)	104 (14%)	22 (3%)
Madagascar	292	11 (4%)	281 (96%)	252 (86%)	234 (80%)
Nearctic	189	41 (22%)	148 (78%)	146 (77%)	113 (60%)
Neotropic	1972	1426 (72%)	546 (28%)	440 (22%)	282 (14%)
Oceania	507	284 (56%)	223 (44%)	186 (37%)	155 (31%)
Oriental	1065	772 (72%)	293 (28%)	206 (19%)	158 (15%)
Palearctic	573	245 (43%)	328 (57%)	301 (53%)	243 (42%)
Overall	6304	4004 (64%)	2300 (36%)	1941 (31%)	1450 (23%)

- Ecology: *Activity time* was treated as a trichotomy, with species being considered nocturnal, diurnal, or cathemeral. The *substrate* of species was considered as surface active, fossorial or aquatic, with semi-fossorial and semi-aquatic species considered fossorial and aquatic, respectively. *Leg reduction*: we treated species as either fully-legged (if they have four pentadactyl limbs) or as leg-reduced (if they possess no legs, or have reduced number of digits). *Reproductive mode*: was treated as a viviparous (including ovoviviparous species)/oviparous dichotomy. We omitted species with a mixed oviparous/viviparous reproduction from analyses of reproductive mode.
- Life history: *Body size* is the maximum weight of a species as derived from maximum snout-vent length (SVL) by means of clade-specific allometric equations (Meiri, 2010; Novosolov et al., 2013; Scharf et al., 2015; Feldman et al., 2016). *Clutch size* is the mean clutch or litter size per species. If multiple means were reported we used the mid-point of means. If there are no means then we used the midpoint of observations (i.e., [smallest clutch + largest clutch]/2). *Longevity* is the maximum recorded longevity of a species (see Scharf et al., 2015 and references therein).
- Phylogeny: *Lizard family*, *lizard lineage*, *taxonomic group* (Sauria or Amphisbaenia), and *year of description* were obtained from the reptile database (Uetz and Hosek, 2015).

In some cases where we had no direct data for traits, we deciphered them from the traits of family members (when families were homogenous for a trait state, or nearly so) in the following manner: all chameleons, agamids, lacertids, teiids, varanids, cordylids, and iguanians with no activity time data were assumed to be diurnal unless other information exists (data were imputed for 22% of species). All amphisbaenids and dibamids were considered fossorial unless other data existed (data were imputed for 58% of species). All geckos, chameleons, lacertids, liolaemids, polychrotids, leiocephalids, and phrynosomatids were considered as surface-active unless other data existed (data were imputed for 17% of species). All agamids, lacertids, varanids, geckos (except Diplodactylidae), gerrhosaurids, gymnophthalmids, teiids, tropidurids, leiocephalids, iguanids, anoles, and hoplocercids were assumed to be oviparous unless other information exists (data imputed for 44% of species). All other data represent species-specific values and are not imputed.

2.1. Statistical analyses

We consider four categories for lizard assessments:

1. Species never assessed.
2. Species assessed (by either Böhm et al., 2013, or the IUCN, or both).
3. Species assessed as in #2, but excluding those evaluated as Data Deficient.
4. Species assessed by the IUCN and not by Böhm et al. (2013).

We start with multiple logistic regression models (glm with binomial errors) where the status of assessment ("no" or "yes" according to the categories above) is the response variable.

Because sample sizes for different predictors are highly unequal (see results in Tables 1–8), however, we only used in these model predictors for which we had data for >98% of the species: body mass, realm, range size, and leg development. We identified the best model for this 5-predictor set. Subsequently we tested the influence of the other predictors individually, by adding each one in turn to the best model inferred at the previous stage. In these analyses we did not assess the roles of reproduction mode, which is tightly related to latitude (Feldman et al., 2015), clutch size and longevity (which are strongly affected by body size, Meiri et al., 2012, Scharf et al., 2015).

We then used univariate models, for each predictor in turn, as follows: used two simple tests to identify biases in the assemblage of assessed species, chi-square tests for analyses of frequencies (e.g., the number of assessed vs. non-assessed species in different activity time

categories, viviparous and oviparous species, or families), and t-tests when comparing numeric data (e.g., elevations, body masses). We corrected for mass when analysing longevity and clutch sizes using multiple regression. The analysis of clutch size was repeated for only those taxa with variable clutch size (Meiri et al., 2015) — i.e. all those with a clutch size larger than two eggs, so analyses will not be biased by unequal numbers of geckos, gymnophthalmids, anoles etc. across assessment categories.

Each trait was analysed three times for biases: non-assessed species were compared to assessed species (comparison 1), assessed and non-DD species (comparison 2), and species assessed, but not in Böhm et al.'s (2013) dataset (comparison 3).

We did not attempt to 'correct for' phylogenetic (and spatial) non-independence for three main inter-related reasons: 1. The fact that one uses a multi-species dataset does not automatically mean that the questions should be viewed from a phylogenetic perspective: for some questions such a perspective is simply irrelevant (see Westoby et al., 1995a, 1995b). We are not examining the evolution of extinction risk but the biases in assessing it, a question we think does not lend itself to a phylogenetic analysis. 2. In particular, our question — what does the IUCN assess and what it does not is exactly the type of question that does not lend itself to phylogenetic analyses. This is because extinction risk does not evolve in the way species do: it is mostly imposed on species through anthropogenic pressure, which is unlikely to mirror the course of the phylogeny of a specific group. Species do not share their extinction risk from a common ancestor. There may be traits that predispose species to be at risk — and these may have a phylogenetic signal, but the single trait that is relied most heavily on when assessing species (range size, the B criteria) is probably the trait that is under the weakest phylogenetic inertia (range sizes are also not shared from a common ancestor, are much more labile than most traits, and often have little if any phylogenetic signal (e.g., Diniz-Filho and Torres, 2002; Raia et al., 2011). 3. Correcting for phylogeny risks throwing the baby out with the bath water — we may be correcting for the very bias our analyses are trying to uncover (Hansen and Orzack, 2005; Labra et al., 2009). Phylogenetic and spatial biases are 'built into' the way the IUCN goes about its business of assessing species (see also Roll et al., 2016–in this issue). The very existence of specialist groups ensures this - hence, for example, most iguanas are assessed, but few amphisbaenians are because there is no amphisbaenians specialist group. The other way the IUCN assesses species by is analysing the entire reptile fauna of a region, which also means only a phylogenetically and spatially biased subset of all taxa will be assessed. Thus should we 'correct' for phylogeny we posit we will be 1. Asking a different question than we aim to answer here and 2. Lose the pattern that we set to identify: after correcting for the bias in the IUCN assessments we are unlikely to find that these assessments are biased — but they are.

3. Results

3.1. Distribution

The IUCN have assessed a combined total of 2300 lizard species, leaving 4004 non-assessed species (Table 1). The number of assessed species varied significantly among biogeographic realms ($P < 0.0001$ for all three comparisons; Table 1, Fig. 1). Australia had the lowest percentage of assessed species (15%), followed by the Neotropic, Oriental, and Afrotropic realms. Madagascar had near complete assessment (Jenkins et al., 2014) and the Nearctic had a high assessment rate (Fig. 1). Across the eight realms the proportion of non-assessed species increases with the overall (log transformed) number of species within realms ($R^2 = 0.655$, $P = 0.015$). The proportion of assessed species likewise differed among biomes ($P < 0.0001$ for all three comparisons), with montane, temperate and tropical biomes the least well assessed (Table 2). Contrary to our prediction, deserts were the second best-assessed biome behind the Mediterranean (Table 2).
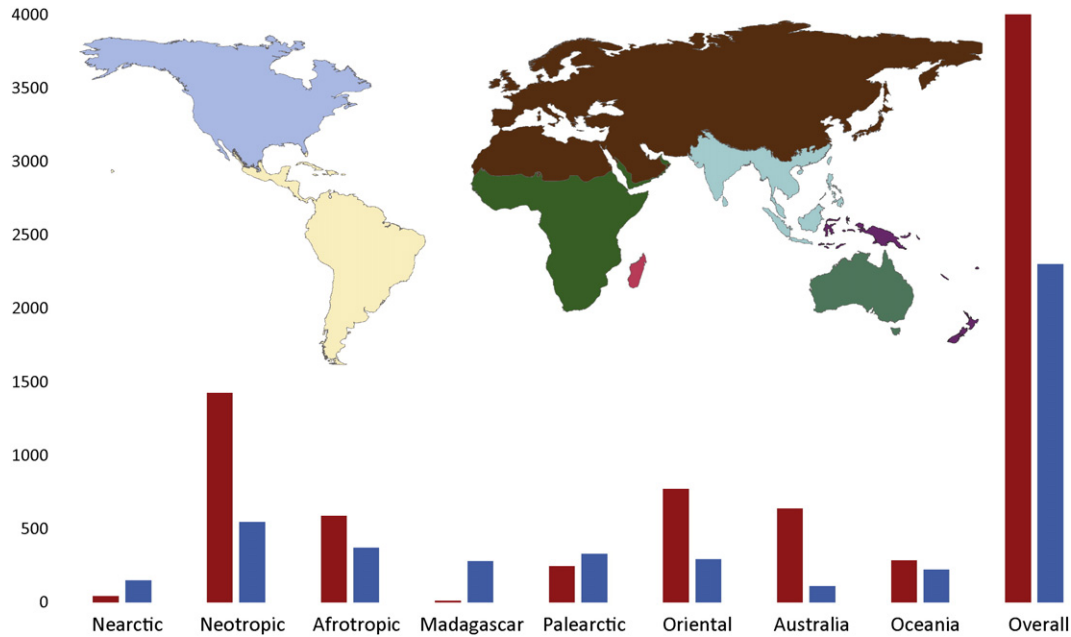
Fig. 1. The numbers of assessed (blue) and non-assessed species (red) in each biogeographic realm, and globally ("overall"). The y axis represents species numbers. Realms are the Nearctic (light blue), Neotropic (pale yellow), Palearctic (brown), Afrotropic (green), Madagascar (pink), Oriental (turquoise), Australia (pale green), and Oceania (purple).

Assessed lizard species have larger range sizes, and occur at more northerly latitudes, than non-assessed species ($P < 0.0001$ for all three comparisons; Table 3). In addition, assessed lizard species occur over broader elevational ranges ($P < 0.0001$ for all three comparisons) but, contrary to our prediction, non-assessed species actually occurred at lower maximum elevations ($P < 0.0001$ for comparisons 1 and 2, $P = 0.0002$ for comparison 3; Table 3). Assessed lizard species were more likely to be insular endemics compared to non-assessed species ($P < 0.0001$ for all three comparisons; Table 4).

3.2. Ecology

Nocturnal species have lower rates of assessment than diurnal or cathemeral species for comparisons 1 and 2 (comparison 1: $\chi^2 = 8.6$, $P = 0.01$; comparison 2: $\chi^2 = 12.9$, $P = 0.002$), but this was marginally non-significant for comparison 3 ($\chi^2 = 5.0$, $P = 0.08$) (Table 5). Surface active lizard species are more likely to have their conservation status assessed compared to fossorial or semi-aquatic species (comparison 1: $\chi^2 = 9.8$, $P = 0.008$, comparison 2: $\chi^2 = 14.4$, $P = 0.0007$, comparison 3: $\chi^2 = 19.8$, $P < 0.0001$; Table 5). Viviparous species exhibited higher rates of assessment than oviparous species (comparison 1: $\chi^2 = 117.9$, $P < 0.0001$, comparison 2: $\chi^2 = 8.2$, $P = 0.004$, comparison 3: $\chi^2 = 10.4$, $P = 0.001$; Table 5). Limb reduced and limbless lizard species were less likely to be assessed (comparison 1: $\chi^2 = 10.9$, $P = 0.001$, comparison

2: $\chi^2 = 18.0$, $P < 0.0001$, comparison 3: $\chi^2 = 18.9$, $P = 0.0003$; Table 5).

3.3. Life-history

Assessed species tend to be larger (except for Data Deficient species), with larger clutch sizes (corrected for female size), than non-assessed lizard species ($P < 0.0001$ for all three comparisons in both traits; Table 6). However, except for comparison 3 (t = 2.19, $P = 0.029$), there was little evidence for assessed and non-assessed species differing in their longevity (comparison 1: t = 1.60, $P = 0.11$; comparison 2: t = 1.66, $P = 0.10$) (Table 6).

3.4. Phylogeny and taxonomy

Non-assessed and Data Deficient species have been described more recently than assessed species ($P < 0.0001$ for all three comparisons; Table 7). The level of assessment varied significantly among the 42 lizard families ($P < 0.0001$ for all three comparisons; Table 8). The least assessed families (excluding those with fewer than five species) are Hoplocercidae, Polychrotidae, Liolaemidae, Dibamidae, and Amphisbaenidae, whilst the most well assessed groups are Crotaphytidae, Opluridae, Chamaeleonidae, Phrynosomatidae, and Iguanidae (Table 8). Similarly, the degree of conservation assessment differed among the nine main super-familial lizard lineages

Table 2
Levels of lizard assessment among the world's major biomes. Percentages are from the biome totals.

Biome	Total	Non-assessed	Assessed		
			Total assessed	Assessed, not DD	Assessed, but not in Böhm et al. (2013)
Deserts and xeric	902	499 (55%)	403 (45%)	363 (40%)	246 (27%)
Flooded grasslands/savannas	8	7 (87%)	1 (13%)	1 (13%)	1 (13%)
Mangrove	36	20 (56%)	16 (44%)	13 (36%)	13 (36%)
Mediterranean	253	114 (45%)	139 (55%)	128 (51%)	97 (38%)
Montane	164	119 (73%)	45 (27%)	37 (23%)	20 (12%)
Temperate	397	237 (60%)	160 (40%)	141 (36%)	103 (26%)
Tropical	3058	1786 (58%)	1272 (42%)	1046 (34%)	726 (24%)

Table 3

Distributional biases (range size, elevation, latitude, sample sizes: 6282, 3831 and 6282, respectively) in the lizard species that have had their conservation status assessed. Range size = log range size (km²). Positive latitude refers to the Northern Hemisphere, whilst negative latitude refers to the Southern Hemisphere. All values are reported with 1 standard deviation.

Trait	Not assessed	Assessed				
		Total assessed	Assessed, not DD	DD	Assessed by the IUCN	Assessed in Böhm et al. (2013)
Range size	3.40 ± 2.01	4.03 ± 1.43	4.15 ± 1.42	3.41 ± 1.37	3.80 ± 1.43	4.43 ± 1.35
Max. elevation (m)	1289 ± 1011	1427 ± 949	1445 ± 945	1313 ± 971	1431 ± 932	1418 ± 980
Elevational range (m)	600 ± 689	821 ± 784	877 ± 791	475 ± 637	816 ± 775	831 ± 801
Latitude	−2.8 ± 20.4	4.6 ± 21.5	4.9 ± 22.1	2.6 ± 17.8	6.6 ± 21.4	1.2 ± 21.3
Absolute latitude	17.4 ± 11.0	19.3 ± 10.5	20.1 ± 9.5	15.2 ± 9.5	19.9 ± 10.1	20.1 ± 10.9

Table 4

Percentage of lizards with insular or mainland distributions that have had their conservation status assessed. Percentages are from the trait totals.

Trait	Not assessed	Assessed				
		Total assessed	Assessed, not DD	DD	Assessed by the IUCN	Assessed in Böhm et al. (2013)
Insular	1017 (54%)	878 (46%)	768 (41%)	110	627 (33%)	251 (13%)
Mainland	2985 (68%)	1425 (32%)	1172 (27%)	253	823 (19%)	602 (14%)
% Insular	25	38	40	30	43	29

($P < 0.0001$ for all three comparisons), with assessment lowest in Dibamidae and Amphisbaenia, and highest in Diploglossa and Acrodontia (Table 8). Sauria species are more highly assessed compared to the Amphisbaenia (comparison 1: $\chi^2 = 7.9$, $P = 0.005$, comparison 2: $\chi^2 = 21.6$, $P < 0.0001$, comparison 3: $\chi^2 = 12.7$, $P = 0.0003$; Table 8).

3.5. Multiple predictor models

The best model for species assessments among those models for which we had data on >98% of species included the effects of range size, insularity and latitude (all positively associated with the probability of assessing a species), as well as of biogeographic realm (species were most likely to be assessed in Madagascar, followed by the Nearctic, with Oriental and, particularly, Australian species the least likely to be assessed. Effects of body size and the degree of leg development were not significant.

Omitting data deficient species body mass emerged as a significant predictor, with assessed species being larger, on average, than non-assessed ones (slope 0.14 ± 0.04, $P = 0.0009$). Omitting the species assessed by Böhm et al. (2013) from the assessed species list (but retaining DD species), all predictors for which we had data on nearly all species are significant. In addition to those depicted above (all with the same signs) leg-reduced species were less likely to have been assessed (slope −0.375 ± 0.138, $P = 0.007$). Activity time and substrate had no effect on the probability of assessment when added as

additional predictors to each of these three models. Species with large clutch sizes, wide elevation ranges and, especially, with high maximum elevations were more likely to be assessed. Furthermore, species were least likely to be assessed in temperate and montane biomes, than in deserts, and more likely to be assessed in the tropics and, especially in the Mediterranean and mangrove biomes. The full results of these models are presented in Appendix 1.

4. Discussion

4.1. Low rate of species assessment is a more pressing concern than data deficiency

Species conservation is a challenging enterprise because management decisions need to be made based on limited, or incomplete, information (Tingley et al., 2013b; Primack, 2014). For terrestrial vertebrate groups with near complete species assessment (83–99% assessment in birds, mammals and amphibians; see Introduction), perhaps the largest unknowns are Data Deficient species; those species that cannot be assigned a threat status due to insufficient knowledge of their distribution, biology or ecology (IUCN, 2015). Consequently, there has been a recent focus on methods and approaches to predict the conservation status of Data Deficient species (Howard and Bickford, 2014; Bland et al., 2015), including in reptiles (Bland and Böhm, 2016–in this issue). Indeed, reptiles (21% of the 1500 species considered in Böhm et al., 2013), and lizards more specifically (16% of assessed species;

Table 5

Ecological biases (activity, reproductive mode, substrate, limb development) in the lizard species that have had their conservation status assessed. Percentages are from the trait totals.

Trait	Not assessed	Assessed				
		Total assessed	Assessed, not DD	DD	Assessed by the IUCN	Assessed in Böhm et al. (2013)
Activity						
Diurnal	2155 (60%)	1421 (40%)	1263 (35%)	158	902 (25%)	519 (15%)
Nocturnal	666 (65%)	354 (35%)	298 (29%)	56	230 (23%)	124 (12%)
Cathemeral	139 (60%)	91 (40%)	88 (38%)	3	57 (25%)	34 (15%)
Reproductive mode						
Oviparous	2923 (64%)	1654 (36%)	1441 (33%)	213	1011 (23%)	643 (15%)
Viviparous	397 (58%)	290 (42%)	251 (30%)	39	187 (22%)	103 (12%)
Substrate						
Surface active	3019 (62%)	1872 (38%)	1618 (33%)	254	1213 (25%)	659 (13%)
Fossorial	413 (68%)	195 (32%)	152 (25%)	43	100 (16%)	95 (16%)
Semi-aquatic	78 (67%)	39 (33%)	38 (32%)	1	25 (21%)	14 (12%)
Limb development						
Non-limb reduced	3551 (63%)	2104 (37%)	1790 (32%)	314	1345 (24%)	759 (13%)
Limb reduced	451 (69%)	199 (31%)	150 (23%)	49	105 (16%)	94 (14%)

Table 6

Life history biases (body size, clutch size, longevity) in the lizard species that have had their conservation status assessed. Clutch sizes are for all species (2nd row; 3271 species) and only for species with variable clutch sizes (3rd row, 1693 species). Longevity data are available for 710 species, mass data for 6286 species. All values are reported with 1 standard deviation.

Trait	Not assessed	Assessed				
		Total assessed	Assessed, not DD	DD	Assessed by the IUCN	Assessed in Böhm et al. (2013)
Body mass (log g)	0.95 ± 0.68	1.04 ± 0.73	1.08 ± 0.74	0.80 ± 0.63	1.06 ± 0.74	1.00 ± 0.72
Clutch size	3.39 ± 3.11	4.64 ± 5.32	4.77 ± 5.47	3.16 ± 2.53	4.96 ± 5.53	4.12 ± 4.92
Variable clutch taxa	5.3 ± 3.7	6.8 ± 6.1	6.9 ± 6.3	5.5 ± 2.6	7.0 ± 6.2	6.5 ± 6.0
Average longevity (years)	9.1 ± 7.7	10.1 ± 9.60	10.2 ± 9.6	7.6 ± 8.05	10.7 ± 10.7	9.0 ± 7.2

this study, Table 1), have higher levels of data deficiency compared to birds (0.6%; Butchart and Bird, 2010), and mammals (15%; Schipper et al., 2008), but lower levels than amphibians (25%; Stuart et al., 2004). Yet, whilst data deficiency is a key knowledge gap in lizards, our study highlights that it is a secondary concern compared to the overall low rate of species assessment.

Nearly two-thirds (64%) of the 6304 known species of lizard have not had their threat status assessed by the IUCN (Table 1). Thus, non-assessed lizard species are an order of magnitude more numerous than those that have been assessed by the IUCN and categorized as Data Deficient (4004 vs. 359 species). More worrying is that this may represent a substantial underestimate of the 'assessment gap', as on-going taxonomic work on the world's lizards indicates that numerous species remain to be described throughout most regions of the world (Uetz and Hosek, 2015). Recent global efforts to obtain a complete picture of the conservation status of the world's reptiles have focused on developing short-cut methods for predicting threat status in Data Deficient (and potentially non-assessed) species (Bland and Böhm, 2016–in this issue), and improving our knowledge of the reptile fauna of understudied regions such as Australia (Rosauer et al., 2016–in this issue), Africa (Tolley et al., 2016–in this issue) and South-east Asia (reviewed in Tingley et al., 2016–in this issue), particularly through regional or taxonomic working groups (e.g., the IUCN's GRA). The present study acts to highlight hotspots of underassessment and allows us to determine whether the drivers of extinction risk gleaned from a select subset of species (Böhm et al., 2013, 2016) are likely to be consistent across the broader lizard fauna.

4.2. Distributional, life history, ecological, and taxonomic biases are evident in the lizard species that have been assessed

Biases exist in the lizard species that have been assessed by the IUCN for almost every trait that we examined. This was true for the 2300 species assessed overall, and the subset included in Böhm et al. (2013). Non-assessed lizard species occur at more southerly latitudes, providing clear support for our prediction that intense research activity in particular regions (e.g., USA and Europe) would result in higher rates of assessment. Similarly, as per our prediction, assessed lizard species had distributions that would make them more readily detected, and more easily studied, by researchers; that is, larger distributional and elevational ranges (although, in contrast to our prediction, they did not occur at lower maximum elevations). As conservation status in reptiles is based primarily on range size (Category B), both on global (Böhm et al., 2013) and regional scales (e.g., New Zealand; Tingley et al., 2013a), the non-assessed lizard species are likely to have higher levels of threat status than those already considered by the IUCN. Thus, numerous (100s or even 1000s) threatened lizard species remain to be

formally assessed, and therefore the plight of lizard species worldwide may be worse than previously reported (Böhm et al., 2013, 2016).

Although rates of conservation assessment were low across the globe (15–78%, except for Madagascar; Table 1, Fig. 1), we found that the Australian and tropical (Neotropics, Afrotropics, Oriental) regions were the main underassessment hotspots for lizards. These regions may be experiencing an extinction risk 'double whammy', as they also represent hotspots of high threat status (tropical regions), small ranges, and data deficiency (Central Africa, South-east Asia) (Böhm et al., 2013). A similar threat is evident in fossorial lizards (under-assessed and Data Deficient; Böhm et al., 2013; this study). Thus, as predicted, lizards from some regions (e.g., Mediterranean, Nearctic) had higher rates of assessment and therefore there is strong justification for prioritizing lizard conservation efforts in tropical regions of the globe. Indeed, such efforts are already underway for some of these regions (e.g., Africa; Tolley et al., 2016–in this issue; Madagascar, Jenkins et al., 2014). In contrast, whilst reptiles on oceanic islands have been identified as having high threat status (Böhm et al., 2013), we found that insular lizards actually had higher levels of conservation assessment compared to those from mainland regions. Conservation underassessment is particularly dire in Australia, where only 15% of lizard species have been assessed by the IUCN. This could be due to the rapid rate of species discovery and description in Australia over the past decade (Uetz and Hosek, 2015), which has been driven by a recent research focus on remote regions of the monsoon wet tropics (reviewed in Rosauer et al., 2016–in this issue) and integrated taxonomic approaches that have uncovered multiple new taxa within existing widespread species (Oliver et al., 2009, 2010; Doughty et al., 2011, 2015). As species that have been known (i.e. described) for longer have higher rates of assessment (this study), the relatively recent discovery of many Australian lizard species has hampered efforts to determine the true conservation status of the fauna. Alternatively, the huge number of lizard species in Australia (Powney et al., 2010; Wilson and Swan, 2013) may have discouraged anyone from undertaking such a task. In contrast, the near complete assessment of the lizard fauna of Madagascar is the result of a recent systematic analysis of the reptiles of the island as part of the GRA (Jenkins et al., 2014).

Non-assessed lizard species are smaller than those that have been assessed by the IUCN. As larger lizards have been demonstrated to have an elevated risk of extinction (Meiri, 2008; Tingley et al., 2013a; Kemp and Hadley, 2015), body size is seen as a proxy for life history traits (e.g., long-lived species with low clutch frequencies) that might inhibit a species' recovery from population declines. Furthermore, non-assessed lizard species were found to have smaller clutch sizes (corrected for female size), but equivalent longevity, to assessed species. As predicted, lizard species that have attributes that make them more obvious and easier to study (e.g., diurnal, surface active, limbed species) had higher rates of assessment (but note the results of the

Table 7

Mean year of description for assessed and non-assessed lizard species.

Trait	Not assessed	Assessed				
		Total assessed	Assessed, not DD	DD	Assessed by the IUCN	Assessed in Böhm et al. (2013)
Year of description	1942	1922	1917	1948	1925	1917

Table 8

Biases in assessment among lizard Families, super-familial lizard lineages, and lizard lineages (Sauria vs. Amphisbaenia). Percentages are from the taxon totals.

Trait	Not Assessed	Assessed				
		Total Assessed	Assessed, not DD	DD	Assessed by the IUCN	Assessed in Böhm et al. (2013)
Families						
Agamidae	327 (71%)	132 (29%)	111 (24%)	21	61 (13%)	71 (15%)
Amphisbaenidae	134 (77%)	40 (23%)	17 (10%)	23	15 (9%)	25 (14%)
Anguidae	38 (31%)	86 (69%)	67 (54%)	19	67 (54%)	19 (15%)
Anniellidae	4 (67%)	2 (33%)	2 (33%)	0	1 (17%)	1 (17%)
Bipedidae	1 (25%)	3 (75%)	3 (75%)	0	3 (75%)	0 (0%)
Blanidae	2 (33%)	4 (67%)	4 (67%)	0	2 (33%)	2 (33%)
Cadeidae	2 (100%)	0 (0%)	0 (0%)	0	0 (0%)	0 (0%)
Carphodactylidae	21 (70%)	9 (30%)	8 (27%)	1	2 (7%)	7 (23%)
Chamaeleonidae	18 (9%)	184 (91%)	174 (86%)	10	148 (73%)	36 (18%)
Cordylidae	49 (74%)	17 (26%)	15 (23%)	2	8 (12%)	9 (14%)
Corytophanidae	4 (44%)	5 (56%)	6 (67%)	0	5 (50%)	1 (11%)
Crotaphytidae	0 (0%)	12 (100%)	12 (100%)	0	9 (75%)	3 (25%)
Dactyloidae	316 (79%)	83 (21%)	68 (17%)	15	24 (6%)	59 (15%)
Dibamidae	19 (83%)	4 (17%)	2 (9%)	2	1 (4%)	3 (8%)
Diplodactylidae	86 (65%)	47 (35%)	42 (32%)	5	32 (24%)	15 (11%)
Eublepharidae	22 (61%)	14 (39%)	13 (36%)	1	11 (31%)	3 (8)
Gekkonidae	673 (64%)	373 (36%)	290 (28%)	83	254 (24%)	119 (11%)
Gerrhosauridae	11 (30%)	26 (70%)	25 (68%)	1	20 (54%)	6 (16%)
Gymnophthalmidae	206 (83%)	41 (17%)	34 (14%)	7	3 (1%)	38 (15%)
Helodermatidae	0 (0%)	2 (100%)	2 (100%)	0	1 (50%)	1 (50%)
Hoplocercidae	18 (95%)	1 (5%)	0 (0%)	1	0 (0%)	1 (5%)
Iguanidae	9 (22%)	32 (78%)	32 (78%)	0	28 (68%)	4 (10%)
Lacertidae	145 (45%)	176 (55%)	159 (50%)	17	134 (42%)	42 (13%)
Lanthanotidae	1 (100%)	0 (0%)	0 (0%)	0	0 (0%)	0 (0%)
Leiocephalidae	23 (79%)	6 (21%)	6 (21%)	0	2 (7%)	4 (14%)
Leiosauridae	24 (73%)	9 (27%)	7 (21%)	2	3 (9%)	6 (18%)
Liolaemidae	246 (84%)	47 (16%)	25 (9%)	22	15 (5%)	32 (11%)
Opluridae	1 (12%)	7 (88%)	7 (88%)	0	6 (75%)	1 (13%)
Phrynosomatidae	23 (16%)	125 (84%)	120 (81%)	5	95 (64%)	30 (20%)
Phyllodactylidae	78 (58%)	56 (42%)	53 (40%)	3	41 (31%)	15 (11%)
Polychrotidae	6 (86%)	1 (14%)	0 (0%)	1	0 (0%)	1 (14%)
Pygopodidae	36 (80%)	9 (20%)	9 (20%)	0	5 (11%)	4 (9%)
Rhineuridae	0 (0%)	1 (100%)	1 (100%)	0	1 (100%)	0 (0%)
Scincidae	1046 (66%)	542 (34%)	452 (28%)	90	344 (22%)	198 (12%)
Shinisauridae	0 (0%)	1 (100%)	1 (100%)	0	1 (100%)	0 (0%)
Sphaerodactylidae	147 (69%)	65 (31%)	60 (28%)	7	29 (14%)	38 (18%)
Teiidae	97 (64%)	54 (36%)	50 (33%)	4	38 (25%)	16 (11%)
Trogonophiidae	2 (33%)	4 (67%)	2 (33%)	2	3 (50%)	1 (17%)
Tropiduridae	102 (80%)	25 (20%)	19 (15%)	7	1 (1%)	25 (20%)
Varanidae	57 (72%)	22 (28%)	19 (24%)	3	9 (11%)	13 (16%)
Xantusiidae	8 (24%)	26 (76%)	18 (53%)	8	22 (65%)	4 (12%)
Xenosauridae	4 (40%)	6 (60%)	5 (50%)	1	6 (38%)	6 (60%)
Lizard lineages						
Acrodontia	345 (52%)	316 (48%)	285 (43%)	31	209 (32%)	107 (16%)
Amphisbaenia	141 (73%)	52 (27%)	27 (14%)	25	24 (12%)	28 (15%)
Dibamidae	19 (83%)	4 (17%)	2 (9%)	2	1 (4%)	3 (13%)
Diploglossa	46 (32%)	96 (68%)	76 (54%)	20	75 (53%)	21 (15%)
Gekkota	1061 (65%)	575 (35%)	475 (29%)	100	374 (23%)	201 (12%)
Lacertoidea	448 (62%)	271 (38%)	243 (34%)	28	175 (24%)	96 (13%)
Platynota	58 (72%)	23 (28%)	20 (25%)	3	10 (12%)	13 (16%)
Pleurodonta	770 (68%)	355 (32%)	302 (27%)	53	188 (17%)	167 (15%)
Scincoidea	1114 (65%)	611 (35%)	510 (30%)	101	394 (23%)	217 (13%)
Sauria vs. Amphisbaenia						
Amphisbaenia	141 (73%)	52 (27%)	27 (14%)	25	24 (12%)	28 (15%)
Sauria	3861 (63%)	2251 (37%)	1913 (31%)	338	1426 (23%)	825 (13%)

multiple regression models). The underassessment of nocturnal species is of particular concern, as nocturnal lizards often inhabit the same niches as invasive rats (Hoare et al., 2007), resulting in elevated threat status in many species (Towns and Daugherty, 1994; Hitchmough et al., 2010; Tingley et al., 2013a). In contrast, viviparous species, which have been predicted to have greater susceptibility to climate change (Sinervo et al., 2010), were found to have higher rates of assessment than oviparous species, perhaps because they often inhabit well-studied northern Holarctic ranges.

As predicted, the assessment of threat status in lizards is taxonomically biased, both in terms of families and supra-lineages. Since there is also a taxonomic bias evident in reptile extinction risk (Tonini et al., 2016–in this issue), our grasp on the plight of lizards may differ markedly among lizard families and lineages. Differences among lizard taxa in the key traits that we examined (i.e. distribution, life history, ecology) are the result of deep phylogenetic divergences (Vitt et al., 2003; Vitt and Pianka, 2005), and have resulted in disparate levels of extinction risk (Böhm et al., 2016) and threat assessment (this study) among families and lineages of lizards. This 'deep history' influences the diversity, distribution and biology of lizard families and lineages, resulting in differing levels of susceptibility to climate change (Sinervo et al., 2010; Böhm et al., 2016–in this issue), and social or cultural 'values' being attached to particular lizard taxonomic groups (Roll et al., 2016–in this issue).

4.3. What can be done to improve the rate of species assessment in lizards?

Since conservation efforts to date have resulted in only 36% of lizard species being formally assessed by the IUCN, completing an additional 4000 + threat assessments represents a daunting task. The situation is accentuated by the rapid rate of new species discovery and description (Uetz and Hosek, 2015), and the fact that many existing assessments require updating. So what do we need to do in order to achieve full assessment of lizard species? We suggest an integrated approach that focuses on four key areas to bridge the 'assessment gap' in lizards:

i) *Working groups for under-assessed regions or taxa.* This is already well under way as part of the IUCN's GRA. An exemplar of this approach is Madagascar, where a series of workshops involving relevant experts lead to the near complete assessment of the islands' 373 reptile species (Jenkins et al., 2014). Similar working groups have been established for African reptiles (Tolley et al., 2016–in this issue), vipers (Maritz et al., 2016–in this issue), Anoline lizards, Chameleon's, Iguana's, and Monitor Lizards (see http://iucn.org/about/work/programmes/species/who_we_are/ssc_specialist_groups_and_red_list_authorities_directory/amphibians_and_reptiles/). Some of these specialist groups have already completed additional assessments, which are currently in the process of being published. We recommend the establishment of such working groups to speed the assessment of Amphisbaenians (e.g., Colli, 2016–in this issue) and the lizard fauna of Australia and the tropics. Importantly, as the progress of these GRA specialist groups has been restricted by a lack of funding, we recommend prioritization of available funding towards these working groups and investigation of additional funding sources.

ii) *Implementing short cut methods for inferring threat status.* Models have recently been developed for reptiles to, based on a limited subset of distributional, ecological or life-history data, predict the threat status of data deficient species (Tingley et al., 2013a; Bland and Böhm, 2016–in this issue). Similar modelling approaches could be used to assign a preliminary threat status to the ~4000 non-assessed lizard species, and other non-assessed reptiles. As highlighted in Tingley et al. (2013a), an additional benefit of this approach is that it can be used to flag species that have been miss-assigned, and help in identifying out-of-date assessments.

iii) *Increased knowledge of lizard distribution, ecology and life history.* Non-assessed and Data Deficient reptile species are often only known from type specimens, or have limited distributional data (both extent of occurrence and temporal trends) (Bland and Böhm, 2016–in this issue). Detailed information on ecology and life history is lacking for a large proportion of lizard species (Grimm et al., 2014). For example, Myhrvold et al. (2015) recently compiled life history data for 21,322 amniote species. That dataset includes nearly all bird and mammal species but only two thirds of reptile species (6576). Yet, even in this restricted list data for traits such as clutch/litter size are missing for 60% of reptile species (~30% for both mammals and birds), female age at maturity is unknown for 96% of reptilian species (60 & 87% for mammals and birds), and body masses are known for 38% of species (94% in mammals, 97% in birds). This lack of crucial life history data has undoubtedly hampered efforts to assign conservation rankings to species. Initiatives such as the GARD (Global Assessment of Reptile Distributions) working group (http://www.gardinitiative.org) therefore have the potential to greatly improve our ability to assign an accurate threat status to the world's lizards.

iv) *Improved methods for species discovery and description.* IUCN threat categories can only be assigned to species that have been formally described. However, in many regions of the world (e.g., New Zealand, Tingley et al., 2013a, 2013b; Chapple and Ritchie, 2013; Venezuela, Rivas et al., 2012; Argentina, Avila et al., 2013; India,

Agarwal et al., 2014; Agarwal and Karanth, 2015; North Africa, Metallinou et al., 2015) there is a large number of undescribed lizard species. Thus, an increased emphasis should be placed on species description, in addition to species discovery (e.g., Rosauer et al., 2016–in this issue). It is only once both this taxonomic and conservation assessment has been completed that we will attain a full appreciation of the diversity, and plight, of the world's lizards.

5. Conclusion

Reptiles represent the most diverse group of terrestrial vertebrates in the world, yet only 36% of the ~6300 lizard species have had their conservation status assessed by the IUCN. Whilst data deficiency is a key concern in both reptiles (21% of assessed species) and lizards (16% of assessed species), the large number of non-assessed lizard species (~4000 species) represents a larger and more pressing issue. Accentuating this 'assessment gap' is the fact that distributional, ecological, life-history and taxonomic biases exist in the subset of lizard species that have been assessed by the IUCN, distorting our understanding of the true plight of lizards. We recommend the implementation of an integrated approach to bridge the 'assessment gap' in lizards, involving regional working groups (e.g., the IUCN's GRA), predictive modelling, enhanced knowledge of lizard distribution and biology, and improved taxonomic methods.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.biocon.2016.03.009.

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