Biological Conservation 311 (2025) 111397

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Assessing gecko susceptibility to international wildlife trade: A novel trait-based framework

Lucy Cash [a,*], Rikki Gumbs [b], Eleanor S. Devenish-Nelson [a]

[a] Department of Biomedical Sciences, University of Edinburgh, Teviot Place, Edinburgh EH8 9AG, Scotland, United Kingdom of Great Britain and Northern Ireland
[b] Zoological Society of London, Regents Park, London NW1 4RY, United Kingdom of Great Britain and Northern Ireland

ARTICLE INFO

Keywords:
Gekkonidae
Reptile conservation
Intrinsic traits
Endemism
Climate change vulnerability assessment
Wildlife trade
International susceptibility assessment

ABSTRACT

International wildlife trade (IWT) drives biodiversity loss, often affecting species before they are formally assessed or well-known, particularly newly described ones. These species can be traded without consequence due to a lack of prior knowledge or legal protection and reptiles, especially geckos, face pressure from the exotic pet and traditional medicine trades.

We developed a Wildlife Trade Susceptibility Framework (WTSF), adapting trait-based methods from climate change vulnerability assessments to evaluate how species traits influence their desirability and exposure to trade. We applied the WTSF to 1886 known gecko species, a group heavily targeted by IWT. The framework identified 48 % of species as highly susceptible to trade. Key traits linked to susceptibility included evolutionary distinctiveness and body mass. Regions with the highest concentrations of susceptible and sensitive species included Madagascar, Southeast Asia, and New Guinea.

A third of the most sensitive gecko species are absent from current trade databases, likely due to low demand, limited accessibility, or effective enforcement. This absence highlights the limitations of existing species knowledge and monitoring in identifying those most at risk from IWT. Our framework provides an early warning system to flag biologically susceptible species before they appear in trade and can be applied across taxonomic groups.

1. Introduction

International wildlife trade (IWT) is a substantial and complex global industry involving the exchange of live animals, animal products, plants, and their derivatives (Hughes et al., 2021; Marshall et al., 2020). The international pet trade alone is worth billions of dollars annually (Hughes et al., 2021) and poses significant threats to biodiversity, contributing to resource depletion and, in severe cases, species extinction (Benitez-Lopez et al., 2017; Morton et al., 2021).

Effective regulation of IWT depends on robust legal frameworks and comprehensive biodiversity data. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) plays a central role in managing trade through listing species on its appendices and implementing quotas and permit systems (Harfoot et al., 2018). However, the effectiveness of CITES is constrained by taxonomic bias, enforcement challenges, and limited coverage of newly described or Data Deficient species (Scheffers, 2023; Marshall et al., 2020). Likewise, biodiversity assessments such as the IUCN Red List of Threatened Species are essential for identifying extinction risk and guiding conservation priorities, but many species remain unassessed or misidentified (Cazalis et al., 2022; Berec et al., 2018). These gaps limit our ability to anticipate and respond to emerging trade-driven threats.

Geckos, one of the most diverse reptile groups with 2362 species globally (Uetz et al., 2020, 2024), play crucial ecological roles including pest control, pollination, and serving as prey (Ellis et al., 2018). Despite this, they are increasingly threatened by wildlife trade, primarily driven by demand for exotic pets and traditional medicine (Marshall et al., 2020). Both legal and illegal markets exert pressure on wild populations, and frequent illegal trade incidents underscore the need for improved protection (Altherr and Lameter, 2020a). Currently, around 8 % of gecko species are CITES-listed, and protections often come only after significant trade impacts (Marshall et al., 2020).

Previous studies have developed models to predict likely trade in reptiles among other taxa (Challender et al., 2022; Marsh et al., 2022), relying on expert led IUCN Red List assessments. As global networks continue to evolve and expand (Marshall et al., 2020), proactive and

* Corresponding author.
E-mail address: Lucy.Cash@ed.ac.uk (L. Cash).

https://doi.org/10.1016/j.biocon.2025.111397
Received 9 January 2025; Received in revised form 22 July 2025; Accepted 24 July 2025
Available online 6 August 2025

adaptive assessment tools are essential. Trait-based approaches developed within Climate Change Vulnerability Assessments (CCVAs), evaluate species' vulnerability based on life-history and ecological traits (Foden et al., 2013; Foden et al., 2018; Pacifici et al., 2015). They are a flexible and cost-effective approach for assessing vulnerability (Weinhäupl and Devenish-Nelson, 2024) and increasingly adapted for broader conservation assessments (Harper et al., 2022). These frameworks offer an opportunity to support policy ad practice by highlighting species for monitoring improving early warning systems potentially informing decisions around species regulation and trade.

Taking inspiration from the CCVA methodology, we present a trait-based Wildlife Trade Susceptibility Framework (WTSF). Our framework applies trait-based principles to wildlife trade, using traits such as body size, and evolutionary distinctiveness, factors linked to desirability and risk in trade (Fukushima et al., 2020). Species traits are fundamental drivers in wildlife trade dynamics, influencing demand by shaping market desirability (Toomes et al., 2023) and mediating susceptibility by determining species' vulnerability to harvesting pressures (Hughes et al., 2023c). Trait-based frameworks offer consistent, repeatable assessments across taxa and regions (Berec et al., 2018) and provide a more comprehensive perspective than models including one predictor only (Dufour et al., 2022).

Our framework serves two key functions: (1) identifying species with traits associated with higher desirability in IWT, and (2) assessing their biological susceptibility to IWT. We applied this framework to geckos, a species-rich group that is highly sought after in trade, though data limitations exist for some species in terms of ecological information and Red List assessments. By combining biological trait data with IWT records from the IUCN, CITES, and LEMIS, our framework acts as an early warning system by enhancing the detection of susceptible species, including those that are poorly known or recently affected by trade. We have also analysed and illustrated spatial patterns to identify any trends in international trade susceptibility among gecko species.

2. Methods

2.1. Data sources

Species trait data were collated from multiple sources, including the Global Assessment of Reptile Distributions (version 1.7; Roll et al., 2017; Caetano et al., 2022), the Reptile Database: Reptile Species Checklist (30 August 2024; Uetz et al., 2024), the RepTraits Database (Oskyrko et al., 2024), the IUCN Red List (IUCN, 2024), and other published literature (see Metadata, Worksheet 5). Evolutionary Distinctiveness (ED) scores were obtained from Gumbs et al. (2024). Trade data were sourced from the IUCN Red List (version 2024-2), the LEMIS Version 1.1.0 (Eskew et al., 2020) dataset (2005–2014; Smith et al., 2017), the CITES Trade Database (version 2024.1), and species-specific literature (see Metadata, Worksheet 5). Trade evidence was restricted to these databases and the primary literature, excluding online sales data.

Spatial data were drawn from the Global Assessment of Reptile Distributions (version 1.7; Roll et al., 2017), the IUCN Red List (version 2024-2), and realm boundaries as defined by Falaschi et al. (2023) (see Table S1, Fig. S1). Discrepancies such as misspellings, taxonomic revisions, and newly described species were identified and resolved. To ensure consistency across all datasets—including trade and IUCN Red List data—species names were standardized to match those in the Reptile Database (Checklist 30 August 2024).

2.2. Trait selection

Trait-based CCVA frameworks evaluate Sensitivity, Adaptive Capacity, and Exposure (Foden et al., 2018; Weinhäupl and Devenish-Nelson, 2024). The WTSF adapts this approach to assess geckos' susceptibility to IWT based on traits that make them both desirable in trade and biologically sensitive. "Susceptibility" refers to the combined influence of intrinsic biological traits (*sensitivity*) and the likelihood of interaction with trade networks (*exposure*).

Traits were grouped under the broader category of Sensitivity, which includes two components: Desirability and Ecological Sensitivity. *Desirability* refers to traits that increase a species' appeal in trade, such as body mass, snout–vent length (SVL), evolutionary distinctiveness (ED), and range size. *Endemism* contributes to both desirability and ecological sensitivity for example, endemic species with restricted ranges may be highly sought after but also more vulnerable to overexploitation (Auliya et al., 2016).

A scoping literature review (Supplementary) identified five traits (T1–T5) that are linked to desirability, sensitivity and trade pressures (Table 1) across all species in the gecko clade, including those with limited or no documented trade, to flag species potentially susceptible to future trade. In species lacking detailed trade records, these trait-based indicators act as biological proxies for trade susceptibility, offering a precautionary means of identifying at-risk species. Although reproductive habits, habitat preferences, and nocturnality were initially considered, they were excluded due to both data limitations and low trait variation. For example, most geckos lay small clutches of 1–2 eggs (Meiri, 2019), and fewer than ten species are viviparous, limiting the usefulness of reproductive mode or output as a predictor of susceptibility. Trade data was filtered for 'Wild' (letter"W") within CITES and LEMIS datasets and also gathered from literature sources (Table 2). This integrated approach enabled a comprehensive evaluation of geckos' susceptibility, considering both biological traits and trade exposure.

All continuous traits were min–max normalized to a 0–1 scale to ensure consistent scaling and comparability. Directionality was aligned so that higher trait values contribute to greater sensitivity within the framework. Traits with an observed or theoretically supported positive association with susceptibility to trade were included. While smaller geographic ranges are often assumed to confer higher presence in trade, our regression analysis found that gecko species with larger ranges were more likely to appear in trade, likely due to greater accessibility or detectability (Robinson and Sinovas, 2018). As such, we retained the observed direction for range size and did not invert the score. This approach ensures that trait effects reflect empirical patterns specific to geckos; however, in other taxa where trade is influenced differently by rarity, the relationship between traits and trade may differ.

Exposure scores integrated normalized metrics from CITES, LEMIS, and literature sources (Table 2), capturing both historic and recent trade records. Although frequency or trade volume was not included, the presence of trade records was treated as indicative of interaction with international trade networks.

CCVA's often face uncertainty due to incomplete species trait data (Pacifici et al., 2015). To address this, we included only species with complete datasets, avoiding imputation methods, as per Oberman and Vink, 2024. Unlike other CCVA's that apply thresholds for missing data (Foden et al., 2013), our approach minimized uncertainty by focusing on full datasets. Confidence levels for trait data were categorized as High, Moderate, or Low (Table S2), based on source reliability and peer-review status (Foden et al., 2018; Gardali et al., 2012). While this approach excluded some species, it highlighted key data gaps and set priorities for future research. The WTSF offers a scalable, replicable method to identify trade-susceptible species, even those currently outside the scope of documented trade.

2.3. Analysis of variables

2.3.1. Trait selection and evaluation

We assessed multicollinearity among species traits using Pearson correlation coefficients and Variance Inflation Factors (VIF). We applied commonly used thresholds of $r > 0.7$ for high correlation and VIF > 5 to indicate collinearity (Dormann et al., 2013). Most trait pairs exhibited low to moderate correlation. Although Snout–Vent Length (SVL) and body mass were moderately correlated ($r = 0.7$; Fig. S2), all VIF values

Table 1
Summary of trait data used in the WTSF with rationale for use and data availability and relevant references.

Sensitivity/desirability			
Trait	Rationale from literature review only	Data availability	Relevant references of link between trait and sensitivity
T1: Body Mass	Larger bodied species more likely traded than smaller. Positive correlation between body size and trade.	Dataset from Roll et al., 2017 and Uetz et al., 2024. Meiri, 2024	Scheffers et al., 2019, Hughes et al., 2023a, 2023b, 2023c
T2: Snout-Vent-Length (SVL)	In connection with body mass larger specimens show positive correlation with the likelihood to be traded. Inclusion allows for comprehensive assessment varying morphological traits present in geckos e.g. *Pygopodidae*	Dataset from Roll et al., 2017; Uetz et al., 2024. Meiri, 2024	Personal communication Jordi Jannsen, 2023; Shai Meiri 2023.
T3: Evolutionary Distinctiveness (ED)	Human activities including trade are impacting on phylogenetic diversity (PD) of species and global hotspots have been identified for trade in PD of reptiles.	Dataset Gumbs et al., 2024	Scheffers et al., 2019, Gumbs et al., 2020 Hughes et al., 2023a, 2023b, 2023c
T4: Range size	Smaller population size and endemic can be desirable to trade. Larger ranges may offer more accessibility for collection.	Roll et al., 2017, IUCN Red List Extent of Occurrence (EOO) shape Files (2024)	Hughes et al., 2023a, 2023b, 2023c; Robinson and Sinovas, 2018.
T5: Endemism to Islands	Species with endemism to islands are more unique and therefore in demand within the exotic pet trade.	Oskyrko et al., 2024	Meiri et al., 2017; Challender et al., 2023

Table 2
Summary of trade data used within *exposure calculation for the WTSF*.

Data source	Description	Key information extracted	Coverage
CITES Trade Database	International records of trade in CITES-listed species	Species name, CITES Appendix listing, years in trade, number of trade records, quantities (import/export) for wild caught species only	International 2000–2025
LEMIS Database	U.S. wildlife import/export records	Species name, years in trade, number of trade records, total quantity for wild caught species only	International 2000–2015
Published Literature	Trade presence/trade likelihood/likely to be affected by trade	Specific gecko species extracted if recorded in trade or found likely to be traded	2000–2025 International
IUCN	Red List Assessments	Use in trade from data set.	International 2000–2025

were below 5 (Table S5), confirming the absence of multicollinearity. Both SVL and body mass were retained because they represent biologically distinct dimensions of morphology and physiology. In particular, SVL varies independently of body mass in several families, such as *Pygopodidae*, where limb reduction and elongation affect body proportions (Meiri, 2019; Norris et al., 2021). The low VIF values confirm that each variable contributes unique information to the model.

To evaluate the relationship between traits and trade presence (1 = traded, 0 = not traded), we performed binary logistic regression. Odds ratios (OR) and 95 % confidence intervals (CI) were calculated to quantify the direction, strength, and precision of each association (Hosmer et al., 2013). Statistical significance was assessed at $p < 0.05$ (Dushoff et al., 2019). Model performance was measured using the Area Under the Receiver Operating Characteristic Curve (AUC), with values >0.8 considered strong (Hosmer et al., 2013).

We then summarized sensitivity and susceptibility scores by family and by biogeographic realm. Mean differences between traded and non-traded species were tested using Welch's *t*-tests, with effect sizes quantified using Cohen's *d*. At the family level, we reported total species, number of highly sensitive species (top 25 % by sensitivity), number traded, and number of highly sensitive traded species.

2.4. Framework design

Our WTSF (Fig. 1) evaluates two dimensions: Sensitivity (comprising Desirability and intrinsic Sensitivity traits) (Table 1) and Exposure (Table 2). We define Desirability (dependent on taxa) as a component of Sensitivity reflecting species traits that may increase their appeal in wildlife trade such as size, vivid coloration, rarity, or tameness. Traits are scored based on species trade occurrence, following the foundation set by CCVA frameworks (Zhang et al., 2019). Our aim was to create a straightforward, consistent trait assessment framework, avoiding subjective threshold decisions common in traditional CCVA's. A literature review (Supplementary) revealed that many CCVA's lack clear justification for their scoring systems (Pacifici et al., 2015), which led us to

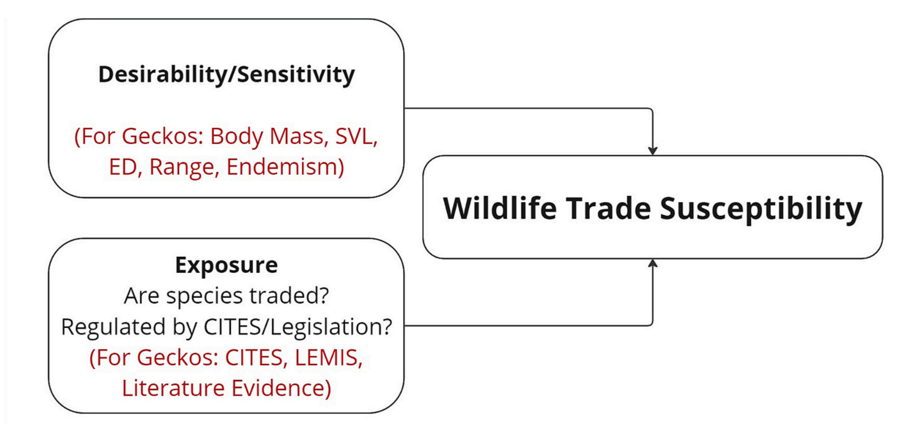

Fig. 1. Structure of the wildlife trade susceptibility framework.

adopt trait normalization to standardize species traits to a 0–1 scale, establishing trait directionality during analysis of variables (Supplementary) and a transparent, generalizable equation for susceptibility.

2.4.1. Calculation of gecko susceptibility

Sensitivity was quantified using five traits: body mass (T1), snout–vent length (T2), ED (T3), geographic range size (T4), and endemism (T5) where T1 to T4 were normalized. Range size (T4) was log-transformed prior to normalization to reduce skewness and limit the influence of outliers (Zuur et al., 2009). Endemism (T5) was treated as binary (0 = not endemic, 1 = endemic). The final Sensitivity Score was calculated as:

$$Sensitivity\ Score = (1)\mathrm{Sensitivity}_i = \frac{(T1_i + T2_i + T3_i + T4_i + T5_i)}{5_i} \quad (1)$$

Exposure to wildlife trade was assessed using three sources for each species. Trade data from CITES (2000–2025) and LEMIS (2000–2015), and literature-derived presence data. CITES data included number of years in trade, trade record count, total quantities, and Appendix listing score. LEMIS data included, years in trade, record count and quantity traded. Literature evidence was compiled from three binary indicators—presence in Challender et al., Hughes et al., and IUCN dataset—and weighted (0.6 for IUCN data, 0.2 each for Challender and Hughes) to create a composite evidence score.

All trade variables were normalized (0–1), and exposure scores were calculated using weighted means across the three sources under different weighting scenarios (e.g., equal weights, CITES-heavy, literature-heavy; see Metadata). The main analysis used equal weights. The final Exposure Score is defined as:

$$Exposure_i Score = 1 + (Cites_i + Lemis_i + Literature\ Evidence_i) \quad (2)$$

where E1 i,E2 i,E 3 i represent binary or continuous indicators, scaled between 0 and 1, of exposure for unit i across different trade data sources or contexts. The constant 1 was added to ensure that units with no recorded exposure still retained a non-zero susceptibility value.

To test the robustness of our susceptibility scoring, we compared results under an alternative exposure weighting scheme (Table S4; Metadata, Worksheet 4). In this version, species with no trade evidence were scored 0; those with any trade indicator (e.g., presence in Challender, Hughes, CITES, or LEMIS) were scored 0.5; and those with evidence and a CITES listing received a score of 1.

Susceptibility was then calculated as the product of sensitivity and exposure:

$$Susceptibility\ Score\ i = Sensitivity\ Score\ i * Exposure\ Score\ i)] \quad (3)$$

This formulation defines each species' biological sensitivity by its level of exposure to trade. Susceptibility Scores are categorized into six levels: Unknown, Very Low, Low, Moderate, High, and Very High Susceptibility, based on an adapted framework from Harper et al. (2022). The susceptibility score value at 25th, 50th, 75th, and 90th percentiles was calculated. This became the fixed lower and upper threshold values for each category allowing for consistent comparisons across analyses and accommodating any skewed data distribution.

Species-level scores showed a right-skewed distribution, with many species scoring low and a minority scoring much higher. Alternative classification methods (e.g., Jenks natural breaks) were tested but did not adequately handle extreme values. Therefore, we used the fixed thresholds based on quantiles (Table 3), balancing interpretability with the data structure. Species classified as Moderate or higher (>0.23) were designated as "Susceptible to Trade" (Fig. 2).

Table 3
Categorization threshold values for WTSF for geckos.

Quantile	Threshold value from data	Final susceptibility category
0–50 %	>0.15 ≤ 0.23	Very low-low
50–75 %	>0.23 ≤ 0.32	Moderate
75–90 %	>0.32 ≤ 0.4	High
>90 %	>0.4	Very high

2.4.2. Spatial analysis

To contextualize and validate results from the WTSF, we conducted a spatial analysis to examine how gecko susceptibility scores are distributed globally. This analysis aimed to identify geographic hotspots and coldspots of susceptibility to wildlife trade, providing insights into spatial patterns of concentrated risk (Fig. S1, Table S2).

Spatial analyses were conducted in R (version 4.1.3; R-Core Team, 2024) using a dataset of 1886 gecko species with georeferenced occurrence points. Species were assigned to a global 5° hexagonal grid using the dggridR package (Barnett, 2021), allowing calculation of species richness, average susceptibility scores, and dominant biogeographic realms per grid cell (based on Falaschi et al., 2023). Species richness was calculated using a 5° resolution (~555 km at the equator), while Getis-Ord Gi* hotspot analysis was performed at a finer 2.5° resolution (~278 km at the equator) to assess local clusters of high and low susceptibility. The localG() function from the spdep (Zurell et al., 2020) and sf (Pebesma, 2024) packages was used to detect significant clusters. Cells with high z-scores indicated susceptibility hotspots, while low z-scores identified coldspots.

2.5. Results

Of the 2362 gecko species in the Reptile Database, 1886 species (79 %, Table S7) were included in the final WTSF analysis, with exclusions due to extinction (5 species) and insufficient trait data (496 species).

2.5.1. Normalization of trait data results

All continuous traits were min–max normalized to a 0–1 scale, with directionality aligned so that higher values contribute positively to sensitivity scores (Methods). In most cases, observed relationships with trade presence matched predictions from prior literature and ecological theory (Table 4). Notably, larger geographic range size—often considered protective—was positively associated with trade (OR = 8.44; see Section 2.5.2), likely reflecting greater accessibility.

2.5.2. Analysis of variables results

The regression model demonstrated moderate predictive performance (AUC = 0.75; Fig. S3). All predictor variables were statistically significant. Evolutionary distinctiveness (ED) (OR = 15.20, 95 % CI: 4.16–56.81, $p < 0.001$) and log-transformed range size (OR = 8.44, 95 % CI: 5.16–13.94, p < 0.001) were strongly positively associated with trade presence. SVL (OR = 8.21, 95 % CI: 1.35–53.92, $p = 0.025$) and body mass (OR ≈ 2.0×10^7, 95 % CI: 1.32×10^4–4.13×10^{10}, p < 0.001) also exhibited large effect sizes.

Body mass was measured in grams and normalized, and the odds ratios reflect the effect of each trait on the odds of trade presence across its observed range. The large odds ratio for body mass is due to its wide variation in body mass across species, not a log transformation. In contrast, range size was both normalized and log-transformed to reduce skew and linearize its relationship with trade presence. Low VIF values for SVL and body mass indicate these effects are not due to collinearity, despite wide confidence intervals.

2.5.3. Sensitivity of Gecko Species

Traded species exhibited significantly higher sensitivity scores (n = 466, mean = 0.286) compared to non-traded species (n = 1420, mean = 0.212), with a significant difference ($p <$ 2.2e−16) and a large effect size (Cohen's d = 0.76). Sensitive traded species included *Rhacodactylus leachianus*, *Lialis jicari*, and multiple species within the genera *Uroplatus* and *Gehyra* (Table 5). At the family level, a high proportion of sensitive species were also traded: 97.7 % (42/43) in *Diplodactylidae*, 88.2 % (15/17) in Eublepharidae, and 34.6 % (110/318) in Gekkonidae (Table S11).

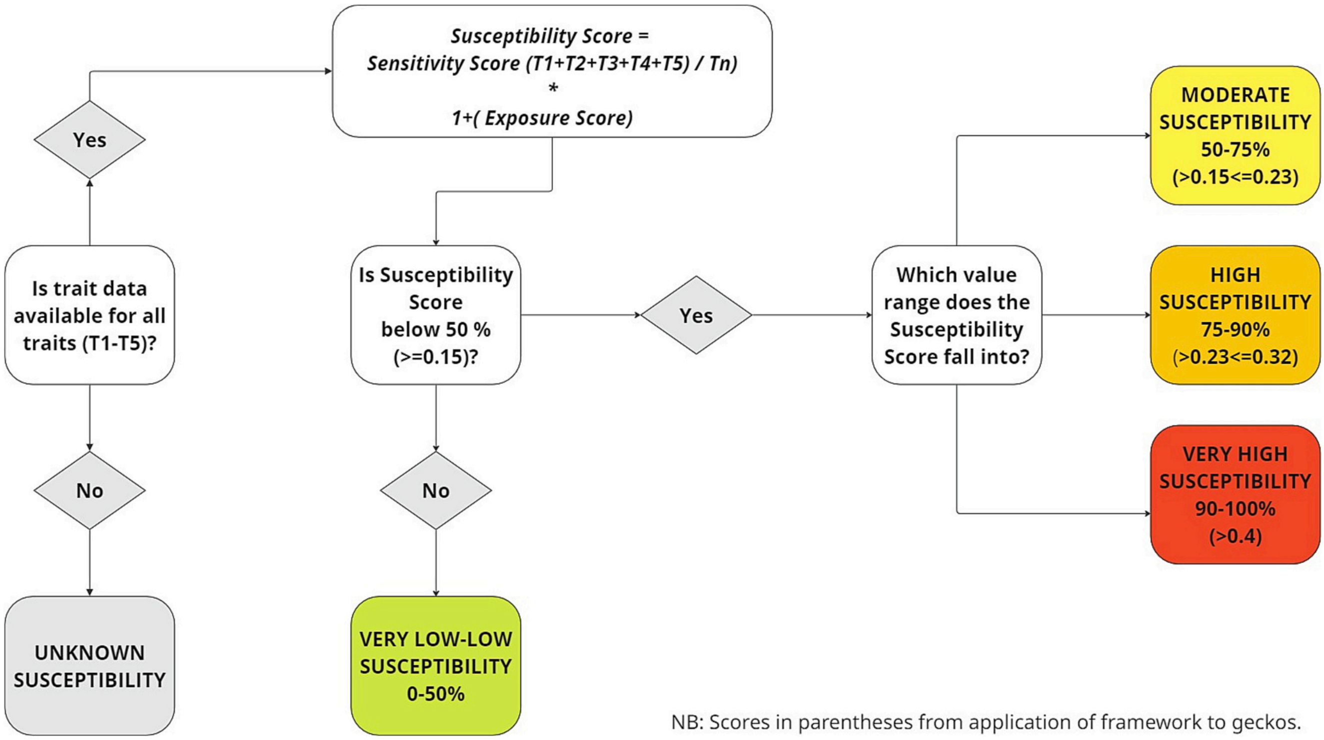

Fig. 2. Structure of final WTSF with susceptibility values for geckos (adapted from Harper et al., 2022).

Table 4
Trait directionality: observed associations with trade presence.

Trait	Predicted direction (from literature)	Observed direction (gecko data study)	Treatment in sensitivity score
T1: Body Mass	Higher = more susceptible	Higher = more susceptible	Retained as-is
T2: Snout–Vent Length	Higher = more susceptible	Higher = more susceptible	Retained as-is
T3: Evolutionary Distinctiveness (ED)	Higher = more susceptible	Higher = more susceptible	Retained as-is
T4: Range Size	Lower = more susceptible	Higher = more susceptible	Log-transformed and retained as-is
T5: Endemism (binary)	Yes = more susceptible	Yes = more susceptible	Retained as-is

2.5.4. *Susceptibility of gecko species*

When analysed, changes among the number of species classified as moderate to very high susceptibility were minimal when using an alternative exposure scoring: moderate decreased by 5.1 %, high by 0.7 %, and very high by 1.5 %. This suggests our framework is robust to alternative exposure scoring methods. Although this secondary weighting was not used in the main analysis, it served as a sensitivity test of the primary approach.

Susceptible species had higher mean values for body mass, SVL, ED, and range size than non-susceptible species (Table 6). Similarly, traded species generally exhibited greater values for these traits than non-traded species, especially for SVL and range (Figs. S4 and S5).

Patterns of susceptibility were comparable for example *Eublepharidae* had the highest mean susceptibility (0.346), with 89.5 % of species in trade. *Diplodactylidae* followed (mean = 0.299; 62.3 % traded), with traded species exhibiting substantially higher scores than non-traded counterparts (0.367 vs. 0.190) (Table S8).

2.6. *Geographic patterns of sensitivity and susceptibility*

Analysis revealed a weak negative correlation between species richness and mean susceptibility score (Fig. S6) using a global rectangular grid of 5° resolution. Susceptible species were distributed across 244 grid cells, with the highest counts concentrated in Madagascar, Central America, Southeast Asia, and Australia (Fig. S7). To explore spatial trends within biogeographic realms, we calculated correlations between log-transformed species richness and average susceptibility per grid cell. These correlations were generally weak and not statistically significant, though a few realms showed moderate trends (e.g., Madagascan: $r = -0.57r = -0.57r = -0.57$; Central American: $r = -0.68r = -0.68r = -0.68$; see Table S6) (Fig. 3).

Using the Getis-Ord Gi* statistic we identified 162 statistically significant hotspots of high susceptibility and 225 coldspots of low susceptibility. Hotspots were mainly located in Southeast Asia, Central Africa, and parts of South America, suggesting significant non-random clustering of high-susceptibility species (Fig. 4). In contrast, coldspots were found across northern North America, northern Eurasia, and parts of Australia. The remaining 261 grid cells exhibited no significant clustering. These spatial trends suggest that species susceptibility to wildlife trade is not randomly distributed, with tropical and subtropical regions generally containing more high-susceptibility species compared to temperate and boreal zones.

Spatial analysis of sensitivity scores revealed among non-traded species, the highest mean sensitivity scores were found in the New Guinean (0.377), Madagascan (0.365), and Oceanian (0.355) realms (Table S10). The Madagascan realm contained the most sensitive species overall (max = 0.521), while the Oriental realm had the most sensitive non-traded species ($n = 98$). Additional hotspots included the Antillean ($n = 33$), Afrotropical ($n = 31$), and Neotropical ($n = 12$) realms, highlighting areas of elevated intrinsic sensitivity beyond documented trade (Fig. S8).

Table 5
Highest scoring susceptible gecko species according to WTSF. CITES Appendices included to show current trade regulations for species. IUCN Threat and Trade Status also included.

Species	Family	Body mass	SVL	ED	Endemic	Range	Traded	CITES	IUCN threat status	Susceptibility score
Rhacodactylus leachianus	Diplodactylidae	478.6	280	19	yes	12,858.52	Y	Not listed	Least concern	0.906542
Uroplatus fimbriatus	Gekkonidae	120.2	195	12	yes	94,206.32	Y	II	Least concern	0.788685
Uroplatus lineatus	Gekkonidae	83.2	170	33	yes	43,154.39	Y	II	Least concern	0.786734
Uroplatus henkeli	Gekkonidae	104.7	186	18	yes	12,389.3	Y	II	Vulnerable	0.75331
Gekko gecko	Gekkonidae	169.8	220	9	no	4,656,213	Y	II	Least concern	0.722529
Phelsuma madagascariensis	Gekkonidae	31.6	120	16	yes	79,710.6	Y	II	Least concern	0.71057
Gekko vittatus	Gekkonidae	47.9	140	18	yes	729,665.9	Y	Not listed	Least concern	0.708937
Lialis jicari	Pygopodidae	24.0	314	5	yes	186,474.5	Y	Not listed	Least concern	0.687284
Gekko kuhli	Gekkonidae	23.4	108	9	yes	1,423,688	Y	Not listed	Least concern	0.652122
Uroplatus sikorae	Gekkonidae	33.9	123	8	yes	88,282.08	Y	II	Least concern	0.650337
Phelsuma standingi	Gekkonidae	43.7	135	26	yes	17,234.09	Y	II	Vulnerable	0.647092
Gehyra vorax	Gekkonidae	109.6	188	22	yes	17,009.29	Y	Not listed	Near threatened	0.638176
Uroplatus phantasticus	Gekkonidae	12.6	86.1	25	yes	44,946.09	Y	II	Least concern	0.634934
Uroplatus ebenaui	Gekkonidae	7.2	70.7	30	yes	28,776.83	Y	II	Vulnerable	0.631161
Rhacodactylus trachyrhynchus	Diplodactylidae	144.5	190	5	yes	5571.33	Y	Not listed	Vulnerable	0.627964
Hoplodactylus duvaucelii	Diplodactylidae	93.3	165	18	yes	86,164.31	Y	III	Near threatened	0.625215
Paroedura picta	Gekkonidae	25.7	111	20	yes	136,497.3	Y	Not listed	Least concern	0.617442
Phelsuma lineata	Gekkonidae	5.8	65	3	yes	224,353.1	Y	II	Least concern	0.612367
Eublepharis fuscus	Eublepharidae	416.9	252	16	no	76,782.37	Y	Not listed	Least concern	0.610371

Table 6
Mean trait values (normalized) for susceptible vs. non-susceptible and traded vs. non-traded species.

Group	Species (N)	Body mass	SVL	ED	Range	Endemic
Non-susceptible	967	0.0112	0.129	0.0989	0.323	0.33
Susceptible	919	0.0312	0.211	0.15	0.66	0.37
Non-traded	1420	0.0146	0.151	0.117	0.453	0.325
Traded	466	0.0403	0.226	0.145	0.593	0.423

3. Discussion

Our analysis revealed complex patterns in gecko species' susceptibility to IWT, highlighting interactions between biological traits, spatial distribution and wildlife trade. The adoption of a novel trait-based approach shows the importance of considering species-specific characteristics when assessing vulnerability (Foden et al., 2013) or in this case susceptibility (Zhang et al., 2019), demonstrating that the concept of interspecific vulnerability, well-documented in climate change contexts for reptiles (Biber et al., 2023; Böhm et al., 2016), is equally relevant to IWT.

3.1. Trait-based susceptibility and trade

Our trait-based analysis revealed a nuanced interplay of biological traits influencing gecko sensitivity to trade. Body mass and SVL also showed strong associations with trade desirability—supporting the idea that larger-bodied species are preferentially targeted (Hughes et al., 2023c). This size-based selection pressure may, over time, exert evolutionary consequences on population structure and life-history strategies (Meeks et al., 2024). While both SVL and body mass significantly contribute to the susceptibility index, we acknowledge potential redundancy due to their correlation. Future iterations of the framework could explore composite indices or allometric corrections (Meiri, 2010) to reduce overemphasis on size while preserving biological relevance.

46 % of traded species exhibited high evolutionary distinctiveness, suggesting that phylogenetically unique species are disproportionately targeted (Hughes et al., 2023b). This is particularly concerning given that the loss of evolutionarily distinct taxa may have disproportionate impacts on phylogenetic diversity and ecosystem resilience (Morton et al., 2021; Gumbs et al., 2024). These findings reinforce previous research suggesting that species with restricted geographic distributions face compounded risks: not only are they inherently vulnerable due to small populations (Meiri, 2019), but they also attract interest in wildlife trade because of their rarity and uniqueness (Hughes et al., 2023a,c).

Although small range size is often associated with desirability (Marshall et al., 2020), only 16 % of susceptible traded species in our dataset had small ranges, compared to 27 % of all small-range species in our dataset, suggesting they are underrepresented in trade. In contrast, widespread species were more frequently traded, indicating that accessibility plays a stronger role in driving trade (Robinson and Sinovas, 2018; Gippet and Bertelsmeier, 2021). While many small-range species exhibited high susceptibility (65 %) and 12 % were traded, their limited accessibility may offer some protection (Altherr and Lameter, 2020a, 2020b), reinforcing the need to consider both range and access in trade risk assessments.

A key limitation of our framework is the lack of explicit aesthetic variables. Traits like bright coloration, unusual morphology, or "exotic" appearance strongly influence market demand in the exotic pet trade (Gippet and Bertelsmeier, 2021; Esmail et al., 2020). While the WTSF includes biological correlates of desirability, it does not quantify visual appeal, which may significantly influence trade, especially in certain taxa. Aesthetic preferences have been shown to shape both legal and illegal trade patterns (Challender et al., 2023). Future iterations could incorporate proxies for aesthetic appeal—such as colour diversity, online trade data, or media presence—to better predict trade susceptibility and guide timely conservation action.

Seventy-nine percent of highly susceptible species are IUCN-listed as threatened (Vulnerable, Endangered, or Critically Endangered), but not included in CITES, suggesting possible regulatory gaps (Hughes et al., 2021). However, CITES is specifically intended to regulate international trade when it directly threatens species survival (Convention on, 2023), so absence from its listings does not necessarily imply oversight. For example, *Gekko gecko*—a heavily traded species—is appropriately listed under Appendix II (Jansen and Chng, 2018). In other cases, non-listing may reflect limited evidence of trade-driven decline. The WTSF can help identify species with high susceptibility yet limited regulatory attention, particularly where biological or trade data are lacking, to inform future IUCN assessments or proactive conservation measures.

While our framework focuses on exposure and biological traits influencing trade susceptibility, it does not directly assess extinction risk as defined by the IUCN (IUCN Standards and Petitions Committee, 2024), which considers broader threats like population decline and habitat loss. Only 11 % of susceptible species in our dataset are IUCN-listed as globally threatened (Vulnerable, Endangered, or Critically Endangered), half of which are documented in trade—suggesting a

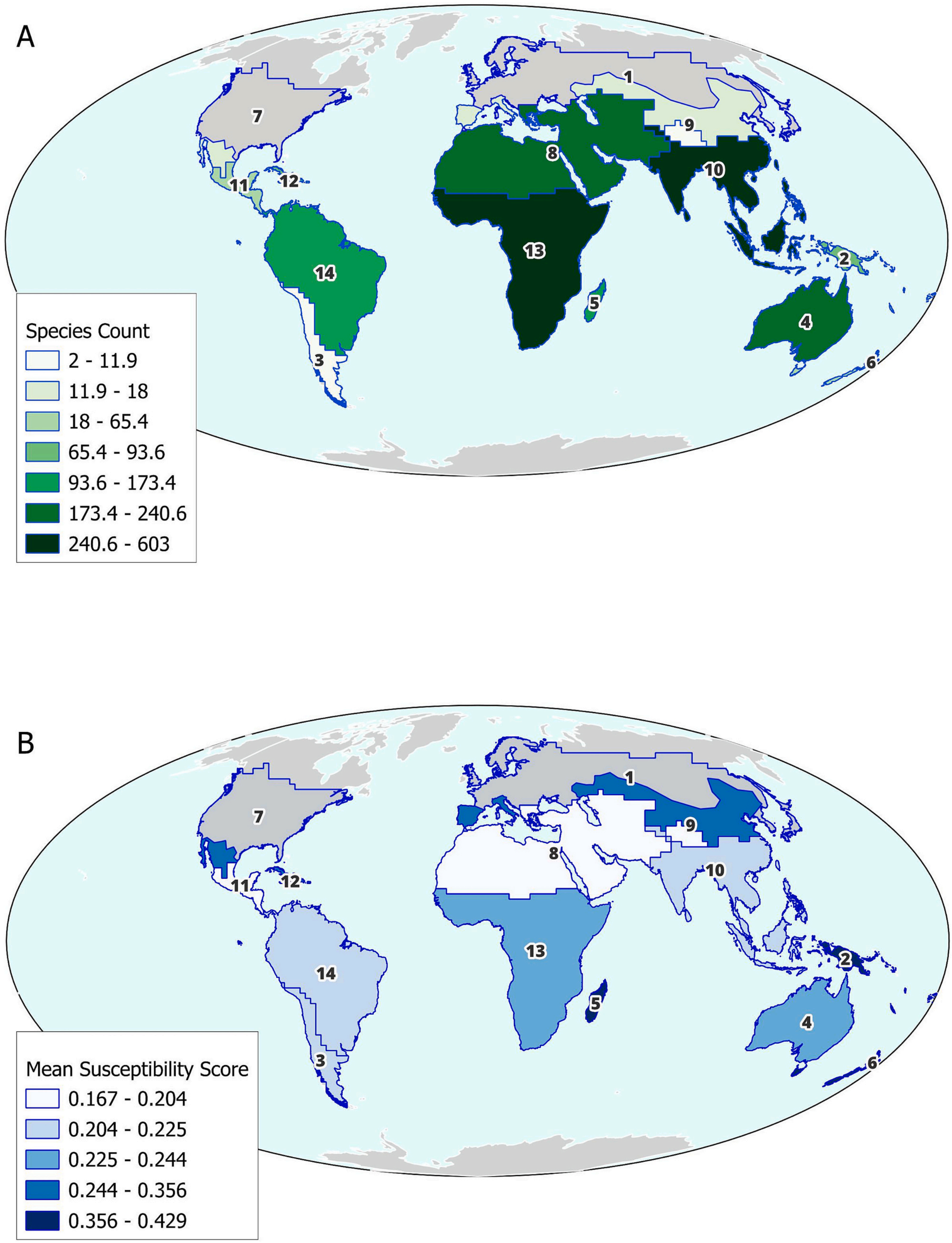

Fig. 3. (A) Species Richness of WTSF Species by Falaschi Reptile realm; (B) average susceptibility scores of WTSF species by Falaschi Reptile realm. (*Falashci Realm detail*, *blue boundary*, *Table S1*). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

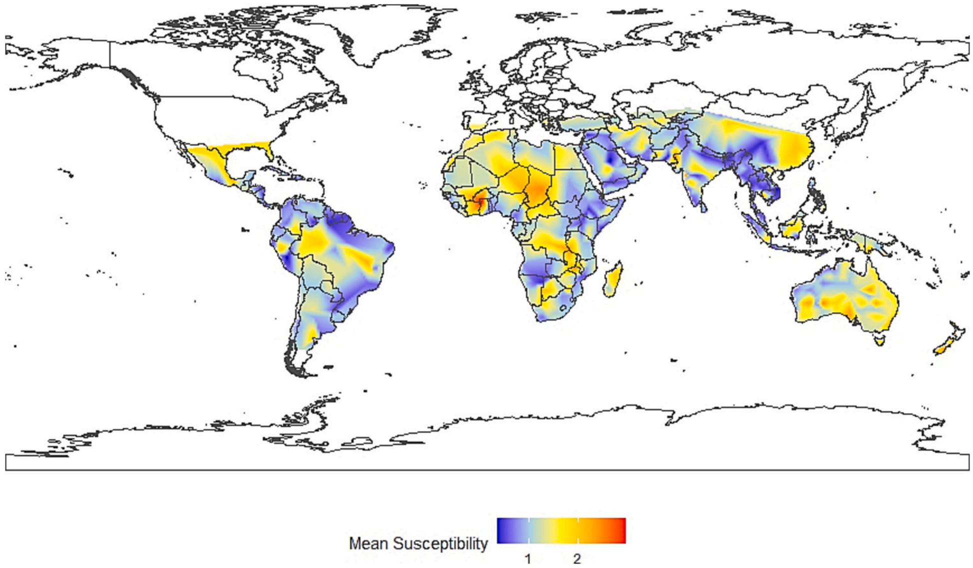

Fig. 4. Getis-Ord G* analysis showing susceptibility hot and cold spots globally, calculated with $n = 1886$ species and Susceptibility Score.

disconnect between trade susceptibility and extinction risk, unlike patterns in other vertebrates (Caetano et al., 2022). This may reflect not a contradiction, but an underestimation of threat in geckos. Around 10 % of susceptible species are Data Deficient or Not Evaluated, supporting concerns that IUCN assessments may overlook emerging risks due to limited data (Challender et al., 2023; Meiri and Chapple, 2016). These results highlight the need for more timely and comprehensive assessments to inform protection of trade-susceptible species.

Trade-susceptible species are unevenly distributed across gecko lineages, with *Diplodactylidae* and *Eublepharidae* showing especially high sensitivity: nearly all highly sensitive species in these families are documented in trade, reflecting a convergence of biological susceptibility and market demand (Esmail et al., 2020). While Gekkonidae has a lower proportion of traded species, its high species richness results in a large absolute number of sensitive, traded taxa. Moreover, several species not currently documented in trade exhibit high intrinsic sensitivity, highlighting the need for proactive conservation attention (Challender et al., 2023), as such species may be at future risk if trade pressures emerge. The higher average sensitivity observed among traded species suggests that intrinsic sensitivity may predispose species to exploitation—or that trade disproportionately targets more susceptible taxa.

Trait and spatial patterns of susceptibility offer opportunities for targeted conservation. Our findings reveal biological and geographic predictors of trade desirability in geckos, consistent with broader links between life-history traits, biodiversity, and anthropogenic pressures in lizards (Lewin et al., 2016). Susceptibility was non-randomly distributed, with significant clustering ($p < 0.05$) and hotspots in the Oceanian and Madagascan realms—regions of high gecko diversity and trade activity (Marshall et al., 2020). The weak correlation between species richness and susceptibility suggests richness alone poorly predicts trade risk. Oceanian geckos had the highest trade proportion and susceptibility, highlighting island vulnerability. The Oriental realm, with the most traded species, reflects intense trade in biodiversity-rich areas (Caetano et al., 2022). To add context, cross-referencing our susceptible species with Marshall et al. (2020) dataset, which captures nationally, and online traded reptiles revealed 474 WTSF susceptible gecko species identified in our study also appear in Marshall's list. This extensive overlap emphasizes the importance of including multiple trade data sources to better capture the full scope of trade exposure.

The Antillean and Oceanian realms also contained many sensitive but non-traded species, indicating that reliance on trade data alone may miss conservation priorities. Trait-based approaches can help identify species and regions needing attention even without documented trade. Discrepancies between susceptibility and trade may reflect historical trade, other regional threats, or data gaps. As the WTSF relies on CITES (European-focused) and LEMIS (U.S. imports), it captures only part of international trade. Future refinements should include broader datasets to better predict emerging trade risk.

3.2. WTSF performance and improvement

The focus of the WTSF is intrinsic sensitivity and susceptibility to trade rather than a direct measure trade-induced threat of species. Unlike expert-led Red List assessments, the WTSF is data-driven, scalable, and cost-effective. It covers nearly 80 % of global gecko species, offering insight into both general and family-level susceptibility to IWT. Although it does not quantify threat, the framework offers a useful tool to identify species that warrant further assessment and monitoring alongside established threat evaluations.

There are a number of key data limitations that need to be acknowledged that constrain the performance of our framework. Trade datasets—particularly CITES—often suffer from inconsistent taxonomy (Kolby and Weissgold, 2022), while open-access data and enforcement records are limited (Challender et al., 2023), reducing coverage of the full trade scope. Historical records (e.g., LEMIS 2000–2014) are biased toward US and European markets, limiting relevance to current trends (Janssen, pers. comm., 2023). Future versions could incorporate real-time data from online platforms and social media, using machine learning to detect emerging demand (Di Minin et al., 2019).

As with other CCVAs, determining trait weightings and thresholds is a key challenge (Pacifici et al., 2015), compounded by limited research linking reptile traits to trade vulnerability (Carvalho et al., 2010). Including more intrinsic and adaptive traits—like reproductive rate, habitat specialization, and coloration—could improve trait coverage and understanding of life-history trade-offs (Van De Walle et al., 2023; Meeks et al., 2024). Examining these interactions with pressures like habitat loss and climate change may clarify trade drivers. Further, expert panel input, common in CCVAs, could help address data gaps and refine scores (Harper et al., 2022). Aligning WTSF's "exposure" metric with CCVA's "magnitude of impact" (Foden et al., 2013), by incorporating trade intensity, would enhance its utility—though this is constrained by poor data on legal and illegal trade (Marshall et al., 2020; Esmail et al., 2020).

Applying trait-based assessments to newly discovered species—prior to IUCN Red List evaluation—may be particularly important, as early-stage discovery often coincides with heightened exploitation risks in the absence of regulatory protection (Liu et al., 2022; Altherr and Lameter, 2020a, 2020b). By addressing current limitations and incorporating these refinements, the WTSF has the potential to evolve into a more robust and adaptive tool to identify at-risk species and support proactive conservation in the face of dynamic global trade.

3.3. Conservation implications and future recommendations

Our findings underscore the urgent need for conservation frameworks that integrate species' susceptibility to IWT. Conservation efforts often prioritize CITES-listed species (Rivalan et al., 2007), potentially overlooking highly sensitive, unlisted taxa (Marshall et al., 2020). Trait-based approaches like the WTSF offer a proactive means to identify such species. For geckos, targeted action is especially needed in regions showing high sensitivity and susceptibility. Enhanced monitoring and enforcement in these hotspots could help mitigate current and future trade pressures.

Despite its limitations, our WTSF shows strong potential as a predictive tool for identifying species at risk of entering trade, rather than directly predicting species threatened by trade impacts. While developed for geckos, the framework is adaptable to other reptiles and broader vertebrate groups due to its flexible structure and reliance on widely available trait data.

With the inclusion of additional traits, updated trade records, and relevant contextual variables, the WTSF has strong potential to serve as a scalable conservation resource. Its straightforward design facilitates uptake by researchers, practitioners, governments, and NGOs, enabling rapid assessments across diverse taxa and regions. As an early-warning indicator, the framework can help identify species at emerging risk of trade, prioritizing them for monitoring, regulation, or inclusion in national and international trade controls. This proactive capability aligns with global biodiversity policy goals, including the Kunming-Montreal Global Biodiversity Framework (CBD, 2023), supporting Target 4 (sustainable trade), Target 5 (proactive conservation), and Target 9 (addressing drivers of biodiversity loss). By informing decision-making for signatories and stakeholders, the WTSF reinforces conservation planning and trade regulation efforts, enhancing responsiveness to shifting wildlife trade dynamics.

To support practical implementation of the WTSF, several recommendations are proposed. Engaging expert panels and regional stakeholders to refine trait selection, address data gaps, and ensure cross-taxa applicability. Integration of the WTSF with existing conservation databases—such as the IUCN Red List, WiTIS, and CITES assessments—would facilitate broader uptake. Finally, hosting the WTSF as an interactive online platform would enable rapid species assessments and support timely, evidence-based conservation actions.

4. Conclusion

Our study revealed that nearly half of the assessed gecko species have desirable traits that make them susceptible to IWT, including higher body mass, snout-vent length and evolutionary distinctiveness with susceptibility hotspots in Madagascar and Southeast Asia. By adapting CCVA frameworks, this research systematically examines trait-based susceptibility to wildlife trade, addressing large knowledge gaps and highlighting at-risk taxa and regions.

This work represents a significant step forward in integrating wildlife trade data with species vulnerability assessments to guide targeted conservation efforts. By accounting for the complexity of trade and species-specific responses, our findings highlight the importance of trait-based assessments in shaping proactive conservation strategies, strengthening conservation measures, and enhancing enforcement. Our framework offers a novel, comprehensive and effective holistic approach to biodiversity conservation amid growing international wildlife trade pressures.

CRediT authorship contribution statement

Lucy Cash: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Rikki Gumbs:** Writing – review & editing, Conceptualization. **Eleanor S. Devenish-Nelson:** Writing – review & editing, Software, Project administration, Methodology, Formal analysis, Conceptualization.

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.

Acknowledgments

We thank Shai Meiri, Peter Uetz and Jordi Jannsen for their contributions to the initial concept of this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2025.111397.

Data availability

Data will be made available on request.

References

Altherr, S., Lameter, K., 2020a. The rush for the rare: reptiles and amphibians in the European Pet Trade. Animals (Basel) 10 (11). https://doi.org/10.3390/ani10112085 [Online] Available at:
Altherr, Sandra, Lameter, Katharina, 2020b. Stolen Wildlife III. https://doi.org/10.13140/RG.2.2.33699.68642.
Auliya, M., Altherr, S., Ariano-Sanchez, D., Baard, E.H., Brown, C., Brown, R.M., Cantu, J.-C., Gentile, G., Gildenhuys, P., Henningheim, E., Hintzmann, J., Kanari, K., Krvavac, M., Lettink, M., Lippert, J., Luiselli, L., Nilson, G., Nguyen, T.Q., Nijman, V., Parham, J.F., Pasachnik, S.A., Pedrono, M., Rauhaus, A., Córdova, D.R., Sanchez, M.-E., Schepp, U., Van Schingen, M., Schneeweiss, N., Segniagbeto, G.H., Somaweera, R., Sy, E.Y., Türkozan, O., Vinke, S., Vinke, T., Vyas, R., Williamson, S., Ziegler, T., 2016. Trade in live reptiles, its impact on wild populations, and the role of the European market. Biological Conservation 204, 103–119. https://doi.org/10.1016/j.biocon.2016.05.017.
Barnett, D.W., 2021. dggridR: Discrete Global Grids for R. R package version 3.0.2.. https://CRAN.R-project.org/package=dggridR.
Benitez-Lopez, A., Alkemade, R., Schipper, A.M., Ingram, D.J., Verweij, P.A., Eikelboom, J.A.J., Huijbregts, M.A.J., 2017. The impact of hunting on tropical mammal and bird populations. Science 356 (6334), 180–183.
Berec, Michal, Vršecká, Lucie, Šetlíková, Irena, 2018. What is the reality of wildlife trade volume? CITES trade database limitations. Biol. Conserv. 224, 111–116. Web.
Biber, M.F., Voskamp, A., Hof, C., 2023. Potential effects of future climate change on global reptile distributions and diversity. Glob. Ecol. Biogeogr. 32, 519–534 [Online] Available at: https://doi.org/10.1111/geb.13646.
Böhm, M., Cook, D., Ma, H., Davidson, A.D., García, A., Tapley, B., Pearce-Kelly, P., Carr, J., 2016. Hot and bothered: using trait-based approaches to assess climate change vulnerability in reptiles. Biol. Conserv. 204, 32–41 [Online] Available at: https://doi.org/10.1016/j.biocon.2016.06.002.
Caetano, G.H.O., Chapple, D.G., Grenyer, R., Raz, T., Rosenblatt, J., Tingley, R., Bohm, M., Meiri, S., Roll, U., 2022. Automated assessment reveals that the extinction risk of reptiles is widely underestimated across space and phylogeny. PLoS Biol. 20 (5), e3001544 [Online] Available at: https://doi.org/10.1371/journal.pbio.3001544.
Carvalho, S.B., Brito, J.C., Crespo, E.J., Possingham, H.P., 2010. From climate change predictions to actions – conserving vulnerable animal groups in hotspots at a regional scale. Glob. Chang. Biol. 16, 3257–3270 [Online] Available at: https://doi.org/10.1111/j.1365-2486.2010.02212.x.
Cazalis, Victor, Di Marco, Moreno, Butchart, Stuart H.M., Akçakaya, H. Reşit, González-Suárez, Manuela, Meyer, Carsten, Clausnitzer, Viola, Böhm, Monika, Zizka, Alexander, Cardoso, Pedro, Schipper, Aafke M., Bachman, Steven P., Young, Bruce E., Hoffmann, Michael, Benítez-López, Ana, Lucas, Pablo M., Pettorelli, Nathalie, Patoine, Guillaume, Pacifici, Michela, Jörger-Hickfang, Theresa, Brooks, Thomas M., Rondinini, Carlo, Hill, Samantha L.L., Visconti, Piero, Santini, Luca, 2022. Bridging the research-implementation gap in IUCN Red List

assessments. Trends Ecol. Evol. 37 (4), 359–370. ISSN 0169-5347. https://doi.org/10.1016/j.tree.2021.12.002.

Challender, D.W.S., Brockington, D., Hinsley, A., Hoffmann, M., Kolby, J.E., Massé, F., Natusch, D.J.D., Oldfield, T.E.E., Outhwaite, W., 'T Sas-Rolfes, M., Milner-Gulland, E.J., 2022. Mischaracterizing wildlife trade and its impacts may mislead policy processes. Conserv. Lett. 15. https://doi.org/10.1111/conl.12832 [Online] Available at:

Challender, D.W.S., Cremona, P.J., Malsch, K., Robinson, J.E., Pavitt, A.T., Scott, J., Hoffmann, R., Joolia, A., Oldfield, T.E.E., Jenkins, R.K.B., Conde, D.A., Hilton-Taylor, C., Hoffmann, M., 2023. Identifying species likely threatened by international trade on the IUCN Red List can inform CITES trade measures. Nat Ecol Evol 7 (8), 1211–1220 [Online] Available at: https://doi.org/10.1038/s41559-023-02115-8.

Di Minin, E., Fink, C., Hiippala, T., Tenkanen, H., 2019. A framework for investigating illegal wildlife trade on social media with machine learning. Conserv. Biol. 33, 210–213. https://doi.org/10.1111/cobi.13104.

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J.R.G., Gruber, B., Lafourcade, B., Leitão, P.J., Münkemüller, T., Mcclean, C., Osborne, P.E., Reineking, B., Schröder, B., Skidmore, A.K., Zurell, D., Lautenbach, S., 2013. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography 36, 27–46. https://doi.org/10.1111/j.1600-0587.2012.07348.x.

Dufour, P.C., Miot, E.F., So, T.C., Tang, S.L., Jones, E.E., Kong, T.C., Yuan, F.L., Sung, Y.-H., Dingle, C., 2022. Home and hub: pet trade and traditional medicine impact reptile populations in source locations and destinations. Proc. R. Soc. Lond. B Biol. Sci. 289. https://doi.org/10.1098/rspb.2022.1011.

Dushoff, J., Kain, M.P., Bolker, B.M., 2019. I can see clearly now: reinterpreting statistical significance. Methods Ecol. Evol. 10, 756–759 [Online] Available at: https://doi.org/10.1111/2041-210x.13159.

Ellis, Ryan, Doughty, Paul, Bauer, A., 2018. An annotated type catalogue of the geckos and pygopods (Squamata: Gekkota: Carphodactylidae, Diplodactylidae, Gekkonidae, Pygopodidae) in the collection of the Western Australian Museum. Rec. West. Aust. Mus. 33, 51–94. https://doi.org/10.18195/issn.0312-3162.33(1).2018.051-094.

Eskew, E.A., White, A.M., Ross, N., Smith, K.M., Smith, K.F., Rodríguez, J.P., Zambrana-Torrelio, C., Karesh, W.B., Daszak, P., 2020. United States wildlife and wildlife product imports from 2000–2014. Scientific Data 7. https://doi.org/10.1038/s41597-020-0354-5.

Esmail, N., Wintle, B.C., t Sas-Rolfes, M., Athanas, A., Beale, C.M., Bending, Z., Dai, R., Fabinyi, M., Gluszek, S., Haenlein, C., Harrington, L.A., Hinsley, A., Kariuki, K., Lam, J., Markus, M., Paudel, K., Shukhova, S., Sutherland, W.J., Verissimo, D., Milner-Gulland, E.J., 2020. Emerging illegal wildlife trade issues: a global horizon scan. Conservation Letters 13 (4). https://doi.org/10.1111/conl.12715 [Online] Available at:. (Accessed October 2023).

Falaschi, M., Marta, S., Elia, Roll, U., Meiri, S., Ficetola, G.F., 2023. Global bioregions of reptiles confirm the consistency of bioregionalization processes across vertebrate clades. Glob. Ecol. Biogeogr. 32, 1272–1284. https://doi.org/10.1111/geb.13694 (data Accessed: October 2024).

Foden, W.B., Butchart, S.H.M., Stuart, S.N., Vié, J.-C., Akçakaya, H.R., Angulo, A., Devantier, L.M., Gutsche, A., Turak, E., Cao, L., Donner, S.D., Katariya, V., Bernard, R., Holland, R.A., Hughes, A.F., O'Hanlon, S.E., Garnett, S.T., Şekercioğlu, Ç.H., Mace, G.M., 2013. Identifying the world's most climate change vulnerable species: a systematic trait-based assessment of all birds, amphibians and corals. PLoS One 8, e65427 [Online] Available at: https://doi.org/10.1371/journal.pone.0065427.

Foden, W.B., Young, B.E., Akçakaya, H.R., Garcia, R.A., Hoffmann, A.A., Stein, B.A., Thomas, C.D., Wheatley, C.J., Bickford, D., Carr, J.A., Hole, D.G., Martin, T.G., Pacifici, M., Pearce-Higgins, J.W., Platts, P.J., Visconti, P., Watson, J.E.M., Huntley, B., 2018. Climate change vulnerability assessment of species. WIREs Clim. Change 10 (1). https://doi.org/10.1002/wcc.551.

Fukushima, C.S., Mammola, S., Cardoso, P., 2020. Global wildlife trade permeates the Tree of Life. Biol. Conserv. 247, 108503 [Online] Available at: https://doi.org/10.1016/j.biocon.2020.108503.

Gardali, T., Seavy, N.E., Digaudio, R.T., Comrack, L.A., 2012. A climate change vulnerability assessment of California's at-risk birds. PloS One 7, e29507 [Online] Available at: https://doi.org/10.1371/journal.pone.0029507.

Gippet, J.M.W., Bertelsmeier, C., 2021. Invasiveness is linked to greater commercial success in the global pet trade. Proceedings of the National Academy of Sciences 118 (14). https://doi.org/10.1073/pnas.2016337118 [Online] Available at:

Gumbs, R., Williams, R.C., Lowney, A.M., Smith, D., 2020. Spatial and species-level metrics reveal global patterns of irreplaceable and imperiled gecko phylogenetic diversity. Israel Journal of Ecology and Evolution 66 (3–4), 239–252 [Online] Available at: https://doi.org/10.1163/22244662-bja10020.

Gumbs, R., Scott, O., Bates, R., et al., 2024. Global conservation status of the jawed vertebrate tree of life. Nat. Commun. 15, 1101. https://doi.org/10.1038/s41467-024-45119-z, 2024.

Harfoot, M., Glaser, S.A., Tittensor, D.P., Britten, G.L., McLardy, C., Malsch, K., Burgess, N.D., 2018. Unveiling the patterns and trends in 40 years of global trade in CITES-listed wildlife. Biol. Conserv. 223, 47–57. https://doi.org/10.1016/j.biocon.2018.04.017.

Harper, J.R.M., van Wilgen, N.J., Turner, A.A., Tolley, K.A., Maritz, B., Clusella-Trullas, S., da Silva, J.M., Cunningham, S.J., Cheney, C., de Villiers, A.L., Measey, J., Foden, W., 2022. Application of a trait-based climate change vulnerability assessment to determine management priorities at protected area scale. Conservation Science and Practice 4 (8). https://doi.org/10.1111/csp2.12756 [Online] Available at:

Hosmer, D.W., Lemeshow, S., Sturdivant, R.X., 2013. Applied Logistic Regression, 3rd ed. Wiley.

Convention on, 2023. International Trade in Endangered Species of Wild Fauna and Flora (CITES). https://cites.org/eng/disc/text.php#II.

Convention on Biological Diversity: 2030 Targets (with guidance notes). Accessible at, 2023. https://www.cbd.int/gbf/targets.

Hughes, A.C., Marshall, B.M., Strine, C.T., 2021. Gaps in global wildlife trade monitoring leave amphibians vulnerable. Elife 10. https://doi.org/10.7554/eLife.70086 [Online] Available at:

Hughes, A., Auliya, M., Altherr, S., Scheffers, B., Janssen, J., Nijman, V., Shepherd, C.R., D'Cruze, N., Sy, E., Edwards, D.P., 2023a. Determining the sustainability of legal wildlife trade. J. Environ. Manage. 341, 117987 [Online] Available at: https://doi.org/10.1016/j.jenvman.2023.117987.

Hughes, L.J., Massam, M.R., Morton, O., Edwards, F.A., Scheffers, B.R., Edwards, D.P., 2023b. Global hotspots of traded phylogenetic and functional diversity. Nature 620 (7973), 351–357 [Online] Available at: https://doi.org/10.1038/s41586-023-06371-3.

Hughes, L.J., Morton, O., Scheffers, B.R., Edwards, D.P., 2023c. The ecological drivers and consequences of wildlife trade. Biol. Rev. Camb. Philos. Soc. 98 (3), 775–791 [Online] Available at: https://doi.org/10.1111/brv.12929.

IUCN, 2024. The IUCN Red List of Threatened Species. Version 2024-2. https://www.iucnredlist.org. Accessed on [October 28th].

IUCN Standards and Petitions Committee, 2024. Guidelines for Using the IUCN Red List Categories and Criteria. Version 16. Prepared by the Standards and Petitions Committee. Downloadable from. https://www.iucnredlist.org/documents/RedListGuidelines.pdf (Accessed data: October 2024).

Jansen, H., Chng, S.C.L., 2018. Biological Parameters Used in CITES Trade Assessments for Eight Reptile Species. TRAFFIC, Cambridge, UK.

Kolby, J.E., Weissgold, B.J., 2022. Exaggeration of the US role in the international tiger trade: response to Khanwilkar et al. (2022). Conserv. Sci. Pract. 4. https://doi.org/10.1111/csp2.12723.

Lewin, Amir, et al., 2016. Patterns of species richness, endemism, and environmental gradients of African reptiles. J. Biogeogr. 43, 2380. https://doi.org/10.1111/jbi.12848.

Liu, J., Slik, F., Zheng, S., Lindenmayer, D.B., 2022. Undescribed species have higher extinction risk than known species. Conserv. Lett. 15 (3). https://doi.org/10.1111/conl.12876.

Marsh, S.M.E., Hoffmann, M., Burgess, N.D., Brooks, T.M., Challender, D.W.S., Cremona, P.J., Hilton-Taylor, C., De Micheaux, F.L., Lichtenstein, G., Roe, D., Böhm, M., 2022. Prevalence of sustainable and unsustainable use of wild species inferred from the IUCN Red List of Threatened Species. Conserv. Biol. 36. https://doi.org/10.1111/cobi.13844.

Marshall, B.M., Strine, C., Hughes, A.C., 2020. Thousands of reptile species threatened by under-regulated global trade. Nat. Commun. 11 (1), 4738. https://doi.org/10.1038/s41467-020-18523-4.

Meeks, D., Morton, O., Edwards, D.P., 2024. Global dynamics of functional composition in CITES-traded reptiles. Ecol. Appl. https://doi.org/10.1002/eap.3060.

Meiri, Shai, 2010. Length–weight allometries in lizards. J. Zool. 281, 218–226. https://doi.org/10.1111/j.1469-7998.2010.00696.x.

Meiri, S., 2019. What geckos are – an ecological-biogeographic perspective. Israel Journal of Ecology and Evolution 66 (3–4), 253–263. https://doi.org/10.1163/22244662-20191075.

Meiri, Shai, 2024. <scp>SquamBase</scp>—a database of squamate (Reptilia: Squamata) traits. Global Ecology and Biogeography. https://doi.org/10.1111/geb.13812. Journal-article. (Accessed data: October 2024).

Meiri, Shai, Chapple, David G., 2016. Biases in the current knowledge of threat status in lizards, and bridging the 'assessment gap'. Biol. Conserv. 204, 6–15. Web.

Meiri, S., et al., 2017. Extinct, obscure, or imaginary: the lizard species with the smallest ranges. Divers. Distrib. 24 (2), 262–273. https://doi.org/10.1111/ddi.12678.

Morton, O., Scheffers, B.R., Haugaasen, T., Edwards, D.P., 2021. Impacts of wildlife trade on terrestrial biodiversity. Nat. Ecol. Evol. 5, 540–548. https://doi.org/10.1038/s41559-021-01399-y.

Norris, J., Tingley, R., Meiri, S., Chapple, D.G., 2021. Environmental correlates of morphological diversity in Australian geckos. Glob. Ecol. Biogeogr. 30 (5), 1086–1100.

Oberman, H.I., Vink, G., 2024. Toward a standardized evaluation of imputation methodology. Biom. J. 66, 2200107. https://doi.org/10.1002/bimj.202200107.

Oskyrko, O., et al., 2024. ReptTraits: a comprehensive dataset of ecological traits in reptiles. Sci Data 11, 243. https://doi.org/10.1038/s41597-024-03079-5.

Pacifici, Michela, et al., 2015. Assessing species vulnerability to climate change. Nature Climate Change 5, 215–224. https://doi.org/10.1038/nclimate2448.

Pebesma, E., 2024. sf: Simple Features for R. R package version 1.0–15. https://CRAN.R-project.org/package=sf.

R Core Team, 2024. R: A Language and environment for statistical computing. (Version 4.3.1) [Computer software]. Retrieved from. https://cran.r-project.org (R packages retrieved from MRAN snapshot 2022-01-01) (Accessed data: October 2024).

Rivalan, P., Delmas, V., Angulo, E., Bull, L.S., Hall, R.J., Courchamp, F., Rosser, A.M., Leader-Williams, N., 2007. Can bans stimulate wildlife trade? Nature 447 (7144), 529–530. https://doi.org/10.1038/447529a.

Robinson, J.E., Sinovas, P., 2018. Challenges of analyzing the global trade in CITES-listed wildlife. Conserv. Biol. 32 (5), 1203–1206. http://www.jstor.org/stable/44973995.

Roll, U., et al., 2017. The global distribution of tetrapods reveals a need for targeted reptile conservation. Nat. Ecol. Evol. 1 (11), 1677–1682. https://doi.org/10.1038/s41559-017-0332-2.

Scheffers, B.R., 2023. Species risk assessment informs trade regulation. Nat Ecol Evol 7 (8), 1175–1176. https://doi.org/10.1038/s41559-023-02097-7.

Scheffers, B.R., Oliveira, B.F., Lamb, I., Edwards, D.P., 2019. Global wildlife trade across the tree of life. Science 366 (6461), 71–76. https://doi.org/10.1126/science.aav5327 (Accessed data: October 2024).

Smith, K.M., Zambrana-Torrelio, C., White, A., Asmussen, M., Machalaba, C., Kennedy, S., Lopez, K., Wolf, T.M., Daszak, P., Travis, D.A., Karesh, W.B., 2017. Summarizing US wildlife trade with an eye toward assessing the risk of infectious disease introduction. EcoHealth 14, 29–39. https://doi.org/10.1007/s10393-017-1211-7.

Toomes, Adam, Moncayo, Stephanie, Stringham, Oliver, Lassaline, Charlotte, Wood, Lisa, Millington, Mariah, Drake, Charlotte, Jense, Charlotte, Allen, Ashley, Hill, Katherine, García, Pablo, Mitchell, Lewis, Cassey, Phillip, 2023. A snapshot of online wildlife trade: Australian e-commerce trade of native and non-native pets. Biol. Conserv. 282, 110040. https://doi.org/10.1016/j.biocon.2023.110040.

Uetz, Peter, Slavenko, Alex, Meiri, Shai, Heinicke, Matthew, 2020. Gecko diversity: a history of global discovery. Isr. J. Ecol. Evol. 66, 1–9. https://doi.org/10.1163/22244662-bja10003 (Accessed data: October 2024).

Uetz, P., Freed, P., Aguilar, R., Reyes, F., Kudera, J., Hošek, J. (Eds.), 2024. The Reptile Database http://www.reptile-database.org, (Accessed data: October 2024).

Van De Walle, J., Fay, R., Gaillard, J.-M., Pelletier, F., Hamel, S., Gamelon, M., Barbraud, C., Blanchet, F.G., Blumstein, D.T., Charmantier, A., Delord, K., Larue, B., Martin, J., Mills, J.A., Milot, E., Mayer, F.M., Rotella, J., Saether, B.-E., Teplitsky, C., Van De Pol, M., Van Vuren, D.H., Visser, M.E., Wells, C.P., Yarrall, J., Jenouvrier, S., 2023. Individual life histories: neither slow nor fast, just diverse. Proc. R. Soc. B Biol. Sci. 290. https://doi.org/10.1098/rspb.2023.0511.

Weinhäupl, Carina, Devenish-Nelson, Eleanor S., 2024. Potential impacts of climate change on terrestrial Aotearoa New Zealand's birds reveal high risk for endemic species. Biol. Conserv. 296, 110668. ISSN 0006-3207,. https://doi.org/10.1016/j.biocon.2024.110668.

Zhang, L., Ameca, E.I., Cowlishaw, G., Pettorelli, N., Foden, W., Mace, G.M., 2019. Global assessment of primate vulnerability to extreme climatic events. Nat. Clim. Chang. 9 (7), 554–561. https://doi.org/10.1038/s41558-019-0508-7.

Zurell, D., König, C., Malchow, A.-K., Cabral, J.S., 2020. A standard protocol for reporting species distribution models. Ecography 43 (9), 1261–1277. https://doi.org/10.1111/ecog.04960.

Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology With R. Springer Science & Business Media.