Conservation Blind Spot: The Critical Role of Larval Stage in Assessing Extinction Risk

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Abstract
In an era of severe global biodiversity threats, understanding the link between species' traits and their endangerment helps uncover causes of risk and infer threats to understudied species. Most animals have complex life cycles with distinct stages that may face stage-specific threats. Current conservation frameworks rely heavily on adult traits, potentially misjudging extinction risk. Using Chinese anurans as a model, we integrated functional traits from both adult and tadpole stages to examine their association with extinction risk. We found that body size positively correlates with risk in both stages. Microhabitat use related with extinction risk in tadpoles but shows no significant link in adults. Adult relative tympanum diameter and head length also correlate with extinction risk. These results indicate that species vulnerability is shaped by multi-stage traits, with both shared and stage-specific threats. Conservation based solely on adult traits may fail to accurately assess species threats. We call for integrating a whole-life-history perspective into biodiversity assessment and conservation to more effectively address the global biodiversity crisis.

Key words: Complex life cycles; Anura; Extinction risk; Amphibian conservation; Functional trait

1 Introduction

Human activities are driving global biodiversity loss at an unprecedented rate and scale, placing a vast number of species at risk of extinction (Cowie et al., 2022; Keck et al., 2025). However, not all species are affected equally or in the same manner. Specie with different ecological strategies exhibit marked differences in vulnerability when facing the anthropogenic disturbances (Chichorro et al., 2022). Investigating the relationship between species' traits and extinction risk is of great importance for revealing causes of endangerment and predicting potential threats. On one hand, understanding the relationship between traits and extinction risk helps identify species' characteristics that make it vulnerable, thereby clarifying the causes of their endangerment. For example, body size, as the most fundamental and commonly measured ecological trait, has been shown to be closely related to extinction risk across numerous taxa (Tomiya, 2013; Vilela et al., 2014; Nolte et al., 2019; Cardillo, 2021). The relationships between body sizes and extinction risks varies among different groups. Large species often face higher risks due to low reproductive rates, narrow distributions, or greater susceptibility to human hunting (Keane et al., 2005; Ruland

& Jeschke, 2017). But in some taxa, small species may be more prone to extinction due to smaller geographic ranges, weak dispersal ability or habitat specialization (Owens & Bennett, 2000; Cardillo, 2021). On the other hand, our knowledge of biodiversity remains incomplete. Even for vertebrate groups, a large number of new species are described annually (Uetz et al., 2025; Frost & Darrel, 2026). Existing assessment systems struggle to promptly evaluate the extinction risk of these new species. Understanding the relationship between traits and extinction risk can provide a basis for risk prediction for species that are not yet assessed or are data-deficient (González-del-Pliego et al., 2019).

Exploring the relationship between species' functional traits and extinction risk is very important for biodiversity conservation (Chichorro et al., 2019). However, a long-overlooked issue is that over 80% of described animal species have complex life cycles (Werner, 1988; Phung et al., 2020). In these groups, different life stages are often highly differentiated in morphology, physiology, behavior, and habitat requirements (Moran & Nancy, 1994). According to the adaptive decoupling hypothesis, trait evolution in these stages often faces different selective pressors and shows relative independence (Wollenberg Valero et al., 2017). This hypothesis has been supported in many groups (Phillips, 1998; Sherratt et al., 2017; Goedert & Calsbeek, 2019). It follows that the threats and vulnerabilities a species faces at different stages may also differ. Unfortunately, studies on drivers of extinction risk always rely on adult traits, with minimal attention paid to juvenile or non-adult stages, leading to potential systematic bias in our understanding of a species' overall vulnerability. For instance, in amphibians, which is a typical group with biphasic life cycles, conservation measures that neglect larval stages are often less effective (Nolan et al., 2023). Furthermore, studies have shown that biodiversity hotspots for tadpoles and adults do not overlap, and conservation priority species defined based on a single stage may have great biases in amphibians (Song et al., 2025a). Meanwhile, incorporating traits from life stages other than adults into models allows for the development of more robust statistical associations between traits and threat status, thereby enhancing the effectiveness of biodiversity conservation efforts.

Anuran amphibians serve as an ideal model system for investigating how functional traits across different life stages relate to extinction risk (Phung et al., 2020). As a group characterized by complex life cycles, amphibians exhibit striking differences between adults and their larval stage, also known as tadpoles, in morphology, diet, microhabitat selection, and behavior (McDiarmid & Altig, 1999). Furthermore, with over 40% of amphibian species facing extinction risk, they rank among the most threatened vertebrate groups (IUCN, 2025). The tadpole stage, often marked by high mortality and sensitivity to disturbances, is considered a critical period for amphibian survival (Nolan et al., 2023). Consequently, insufficient understanding of this life stage may hinder effective conservation of the entire group (Nolan et al., 2023). Examining the relationship between functional traits at different life stages and extinction risk in amphibians not only aids in protecting this unique and endangered group but also offers valuable insights for other taxa with complex life histories. Regrettably, most existing research has focused primarily on adult traits (Cooper et al., 2008; Chen et al., 2019; Cardillo, 2021). Although some studies incorporate reproductive traits, the link between tadpole-stage traits and extinction risk remains poorly understood (Chen et al., 2019). At the same time, past conservation efforts have often failed to adequately consider how various threats affect multiple life stages of amphibians, likely reducing the effectiveness of such measures. This limitation observed in amphibians may be widespread across most animal groups with complex life cycles (Faria et al., 2021). Therefore,

using amphibians as a model, the research framework considering information from different life history stages holds broad implications for advancing the conservation of complex life cycles taxa throughout the animal kingdom. It helps address the bias in current conservation programs which are heavily replying on information of adults.

For groups with complex life histories, the lack of data on stages other than adults severely limits the related research. China harbors exceptional amphibian diversity and has accumulated comprehensive, systematic data on species taxonomy, distribution, ecology, and conservation status (Fei et al., 2009a; Fei et al., 2009b; Fei, 2020; Huang et al., 2023; Song et al., 2025a; Song et al., 2025b; Wei et al., 2025; AmphibiaChina, 2026), providing a unique opportunity for integrated analyses of multi-stage traits and extinction risk. Critically, these data include high-resolution continuous functional trait data, which, compared to traditional discrete or categorical variables, can more finely depict variation in species' ecological strategies (Tobias et al., 2022). Based on high-quality data, we will use Chinese anuran species to address two questions by studying the relationship between extinction risk and functional traits of adults and larvae: (1) Are functional traits of both adults and tadpoles correlated with species extinction risk? (2) If correlated, are these associations consistent across different life stages? By comparing correlations between traits and extinction risk across different stages, we aim to evaluate whether the adult-based conservation assessment system adequately reflects the vulnerability of species with complex life histories.

2 Methods

2.1 Data Collection

Extinction risk data were sourced from the China Biodiversity Red List: Vertebrates Volume (2020) (MEP & CAS, 2023), which is the latest species threat category list for species in China currently. Compared to the International Union for Conservation of Nature (IUCN) Red List, this list is updated more timely for Chinese species and additionally covers the threat categories of 42 species. We also assessed the similarity of species assessments between the two lists based on Spearman correlation and reanalyzed the data based on IUCN Red List. Since our aim was to examine relationships between traits and threat status, rather than predicting the threat status of unevaluated species, we excluded species that were data deficient. Following the method of previous studies (Cardillo, 2021), we performed an ordered coding conversion according to the severity of species threat categories: Least Concern (LC) = 0; Near Threatened (NT) = 1; Vulnerable (VU) = 2; Endangered (EN) = 3; Critically Endangered (CR) = 4.

Functional traits can reflect species' interactions with the environment (Violle et al., 2007). We selected eight morphological traits of both adults and tadpole related to locomotion, foraging, and ecological habits from functional trait databases (Huang et al., 2023; Song et al., 2025b). These traits are closely related to the ecological function and performance of species (Table 1). Tadpole traits were collected specifically during Gosner stages 32–40, when taxonomically diagnostic characters remain stable (Haas et al., 2022). Except for body size, all other morphological data were uniformly converted to ratios relative to total length of tadpoles or snout-vent length of adults. In addition to morphological traits, previous studies have shown that microhabitat type is a strong predictor of extinction risk (Seibold et al., 2015). Therefore, we also included microhabitat data for both adults and tadpoles, encoded as dummy variables. Although amphibians typically breed in aquatic environments, most species spend the majority of their lives

outside water. Thus, microhabitat here refers to the primary non-breeding habitat. Adult microhabitats were classified as: arboreal, fossorial, terrestrial, aquatic, and torrential. Tadpole microhabitats were categorized as lentic or lotic. If a species can inhabit multiple microhabitats, all applicable types were annotated. For example, semi-aquatic was coded as being able to inhabit both terrestrial and aquatic habitats. As our purpose was to compare the relationships between adults' and tadpoles' traits and the extinction risk, our analysis did not include environmental variables, such as distribution range size.

Our compiled dataset includes functional trait data for 375 species. The completeness of the trait data is very high, morphological traits ranging from 68.7% to 100%, and information of microhabitat traits covered all adults and 76.5% of tadpoles (Fig. S1). We performed data imputation considering phylogenetic relationships. The phylogenetic data we used came from previous studies (Xu et al., 2024; Song et al., 2025a), covering all Chinese anuran species. First, we calculated the phylogenetic distance matrix for the species based on the phylogenetic tree. Then, through principal coordinates analysis, we extracted the principal coordinates of the phylogenetic distance matrix, merged them with the functional traits. In total, we used 100 axes, which could account 99.4 % of the variances. Missing values were imputed using the R package missForest (Stekhoven, 2022), a random forest–based method proven highly accurate for high-dimensional data with complex, nonlinear interactions (Stekhoven & Bühlmann, 2011; Penone et al., 2014). We used its default configuration: maximum iterations were set to 10; initial fill values used the median for numerical variables and the mode for categorical variables; the random forest contained 100 decision trees, with a minimum leaf node sample size of 1, a minimum sample size for internal node splitting of 2. The algorithm iteratively refines predictions across variables until convergence or the maximum iteration limit is reached.

2.2 Data Analysis

Prior to analysis, we assessed multicollinearity among all trait variables using variance inflation factors (VIFs). The VIF for each variable was below 5, indicating acceptable levels of collinearity (Table S1). We employed phylogenetic generalized least squares (PGLS) models to examine associations between species traits and threat categories. To account for non-independence due to shared evolutionary history, we incorporated a phylogenetic covariance matrix derived from the species tree. Following the method of Swenson (2014) and Revell et al (2022), models were fitted in R using the gls function from the *nlme* package (Pinheiro et al., 2025), under both Brownian motion (BM) and Ornstein–Uhlenbeck (OU) models of trait evolution. To assess the impact of phylogenetic structure on model performance, we also fitted non-phylogenetic generalized least squares (GLS) models. Model performance was compared using Akaike's Information Criterion (AIC). We also repeated the analysis based on the categories of the IUCN Red List.

Additionally, to test if body size of adults and tadpoles were correlated, we examined the correlation between adult snout-vent length and tadpole total length. To correct for phylogenetic non-independence in correlation estimates, we used the corphylo function from the ape package to compute phylogenetically informed Pearson correlations (Paradis & Schliep, 2018). We first assessed this relationship across all species, then repeated the analysis within families containing more than five species.

All data compilation, analysis, and visualization were performed in R version 4.4.1 (R Core Team, 2024). Original files and code are accessible at:

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3 Results

3.1 Threat Status of Chinese Anurans

After excluding species not evaluated or data deficient in the China Biodiversity Red List, 299 species were included in the analysis. Threat status varied markedly among families (Fig. 1). Dicroglossidae exhibited the highest level of threat: 58% of species were classified as Vulnerable (VU) and 18% as Endangered (EN). Megophryidae also faced high threats, with nearly half (48%) of species in threatened categories. 2% species were classified as Critically Endangered, 30% were classified as VU and 16% as EN. In Bufonidae, Ranidae, and Rhacophoridae, the proportion of threatened species were 22%, 25% and 24%, respectively. In contrast, Hylidae and Microhylidae consisted almost entirely of Least Concern (LC) species, with no threatened taxa recorded. Bombinatoridae had no CR or EN species, but 33% species were listed as VU. The results of the Spearman test support a significant correlation between the threat categories assigned in the China Biodiversity Red List and those in the IUCN Red List (Spearman's ρ=0.573, $p < 0.001$, n = 257).

3.2 Extinction Risk Correlates in Adults and Tadpoles

Model comparisons revealed that the OU-based PGLS model provided the best fit for both adult and tadpole datasets (Table 2). In adults, snout-vent length, head length, and tympanum diameter showed significant associations with threat status (Fig. 2A). Specifically, snout-vent length (β = 0.52, $p < 0.01$) and head length (β = 6.86, $p < 0.001$) were positively correlated with threat level, whereas tympanum diameter (β = –5.91, $p < 0.05$) was negatively correlated. Other morphological variables such as head width, eye diameter, and traits about forelimb and hindlimb showed no significant effects. Notably, adult microhabitat types were not significantly associated with extinction risk.

In tadpoles, only total length and lentic microhabitat use showed significant associations (Fig. 2B). Similar to adults, tadpole body size had a significant positive effect (β = 0.40, $p < 0.05$). Lentic habitat type showed a significant negative correlation (β = -0.55, $p < 0.05$), indicating that species which have tadpoles living in lentic environments had relatively lower extinction risk. None of the other traits showed significant correlations. Correlation between adult and tadpole body size was very weak across all species (r = 0.12), with variation among families (Table 3). In the analysis based on IUCN Red List data, the regression coefficients for each trait were similar, but some traits' coefficients were not significant, including adult head length, body size, and tadpole microhabitat type (Fig. S2 & Table S2).

4 Discussion

By integrating functional trait data from both adult and tadpole stages, we reveal statistical associations between multi-stage traits and extinction risk in anurans. The results support that species threat status is related with traits from both life history stages, and the nature of these associations can be different between stages. Given that over 80% of described animal species have complex life histories (Werner, 1988; Phung et al., 2020), and current conservation programs heavily rely on adult information (Faria et al., 2021), our study suggests that neglecting the

vulnerability of non-adult stages may lead to a systematic underestimation of a species' overall extinction risk. Therefore, to better protect biodiversity, multi-stage perspectives must be incorporated into assessment frameworks and conservation planning (Song et al., 2025a; Roehrdanz, 2026).

4.1 Differences in Threats Across Life Stages

Our results confirm that different life stages face distinct threats. Our analysis clearly showed that tadpole microhabitat type was significantly correlated with extinction risk, while adult microhabitat type showed no such association. Specifically, species with tadpoles living in lentic environments (e.g., ponds) faced significantly lower extinction risk. Habitat alteration caused by human activities is a major threat to biodiversity (Keck et al., 2025). Our results indicate that the impact of habitat change differs across life stages. Therefore, focusing only on one stage, such as adults, may underestimate the threats to biodiversity. Tadpoles are more dependent on aquatic environments than adults (McDiarmid & Altig, 1999), making them particularly sensitive to waterbody degradation (Nolan et al., 2023). The significantly lower extinction threat for lentic tadpoles may be because human-induced habitat changes have a lesser impact on lentic habitats. For example, human-dominated environments, including cities and farmlands, are more likely to retain lentic water bodies, such as ponds in urban parks or farmland (Hamer & Parris, 2011; Holzer, 2014). This result suggests that in amphibian conservation, more attention should be paid to protecting larval habitats. We also recommend that tadpole microhabitat sensitivity be considered as an auxiliary indicator in future species extinction risk assessments.

Apart from body size and microhabitat, no other functional traits in tadpoles showed a significant relationship with extinction risk. However, for adults, besides body size, relative tympanum size and head length were also significantly correlated with extinction risk. We found that species with relatively smaller tympanum faced higher extinction risk. Tympanum size is related to acoustic communication in amphibians, and most anurans rely heavily on acoustic communication for reproduction (Schwartz et al., 2001). This finding aligns with evidence that anthropogenic noise causes auditory masking and disrupts reproductive success (Caorsi et al., 2019; Grenat et al., 2019; Grenat et al., 2024). Research also indicates that noise pollution may alter the combination patterns of multiple acoustic characteristics at the community level (Zhao et al., 2025a). Our analysis results imply that interference with acoustic communication may widely impact amphibian survival. This study found that species with relatively smaller tympanum were at higher risk, which may mean that species relying on higher dominant frequency are more vulnerable under noise interference, a mechanism worthy of verification by future experimental ecological studies.

We also detected a significant positive correlation between relative head length and extinction risk. Species with larger relative head length had greater extinction risk. Skull morphology is related to both habitat selection and diets in anurans (Paluh et al., 2020). For example, fossorial species tend to have short, high skulls, while aquatic species often possess elongated, flattened heads. Unfortunately, for the species involved in our study, research on the threat differences faced by species with different relative head lengths is still lacking. Simultaneously, we found that relative head length varied greatly among different families (Fig. S3). In several families with high species richness and many endangered species, relative head length was larger, such as in Megophryidae and Dicroglossidae. Therefore, we cannot completely

rule out the possibility that the relationship between relative head length and extinction risk is because species in these families have larger relative head lengths. Although we corrected for the influence of phylogenetic relationships in the analysis, strong coupling between taxonomic group characteristics and threat status may still leave a signal. Anyway, our study discovered a potential link between adult head length and extinction risk, which can be regarded as a hypothesis worthy of testing in future studies.

Our results clearly indicate that threats differ between adult and tadpole stages in amphibians. These differences suggest that characteristics of different life stages should receive attention in biodiversity conservation. For example, the impact of various human activities on tadpole habitats should receive more focus. Furthermore, it is highly likely that such differences exist in other groups with complex life cycles. Although the vast majority of described animal species have complex life histories, we have a widespread knowledge gap regarding all aspects of stages other than adults (Faria et al., 2021; Nori et al., 2025). This gap may greatly hinder biodiversity conservation policy-making and related research.

4.2 Common Threats Across Life Stages

Despite stage differences in threats, we also identified a common association throughout the life cycle: larger body size is associated with higher extinction risk. Significant positive correlations were observed in both adults and tadpoles. Among various functional traits, body size is the most commonly associated functional traits with extinction risks (Tomiya, 2013; Seibold et al., 2015; Terzopoulou et al., 2015; Verde Arregoitia, 2016). Several mechanisms may explain this pattern. Large species are often preferentially targeted by humans for consumption or trade (Terzopoulou et al., 2015; Verde Arregoitia, 2016; Chichorro et al., 2019). In China, large frogs such as *Quasipaa spinosa*, *Hoplobatrachus chinensis*, and *Rana dybowskii* have suffered severe population declines due to overharvesting (Fei et al., 2009b; Tian et al., 2011; Chan et al., 2014; Zhao et al., 2014). Our results suggest that human harvesting may also threaten species at tadpole stage. Although less common than adults, in many regions tadpoles are also collected for food or traditional medicine (Luo et al., 2023; Liu et al., 2024). Alternatively, as body size is related to a species' resource acquisition, larger species may require more space or resources (Purvis et al., 2000; Chichorro et al., 2019). When the environment is changed or habitat becomes fragmented, difficulties in resource accessibility may also cause species endangerment (Womersley et al., 2024; Ning et al., 2025; Zhao et al., 2025b). This could also be a reason for the positive correlation between body size and extinction risk. Regardless of the exact mechanism, the consistent positive association between size and risk has practical utility. In the absence of detailed life history data, body size can serve as a proxy variable for preliminary risk screening for Chinese amphibians. In extinction risk assessments or conservation priority ranking, species with larger body size, whether adults or tadpoles, should receive more attention.

Of course, we also cannot exclude another hypothesis, which is that adult and tadpole body sizes are correlated. Previous study found a weak correlation between adult and tadpole body sizes, but this correlation varies among different groups (Phung et al., 2020). Among the species involved in this study, adult and larval body sizes showed only a very weak correlation, with a correlation coefficient of only 0.12 (Table 3). Therefore, although we cannot completely rule out the possibility that the relationship between tadpole body size and extinction risk is due to a correlation between tadpole and adult body sizes, our study supports a conservative inference:

species possessing larger tadpoles overall face higher risk, and this risk should not be neglected in conservation planning.

Conclusion

This study demonstrates that extinction risk in Chinese anurans is shaped by functional traits across multiple life stages. On one hand, stage-specific traits reveal unique combinations of threats faced at different life stages. On the other hand, body size, as a cross-stage common trait, is associated with higher extinction risk in both stages. These findings emphasize that focusing solely on the adult stage will underestimate the overall extinction risks of species, limit our understanding of the threats species face, and reduce the effectiveness of biodiversity conservation measures. Based on our results, we recommend incorporating information from different life history stages when assessing species threat status. Although this study is based on anuran species, stage-specific vulnerability likely has broad applicability. Given the large amounts of animal species have complex life histories, we suggest integrating information across all life stages to build more effective frameworks for global biodiversity conservation.

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References

Altig R, Johnston GF (1989) **Guilds of anuran larvae: relationships among developmental modes, morphologies, and habitats**. *Herpetol Monogr* **3** 81-109.

AmphibiaChina (2026) **The database of Chinese amphibians**. http://www.amphibiachina.org/ accessed: January 6, 2026.

Baldo D, Vera Candioti F, Haad B et al. (2014) **Comparative morphology of pond, stream and phytotelm-dwelling tadpoles of the South American Redbelly Toads (Anura: Bufonidae: *Melanophryniscus*)**. *Biol J Linn Soc* **112**. https://doi.org/10.1111/bij.12296

Campos F, Lourenço-de-Moraes R, Rudoy A et al. (2019) **Ecological trait evolution in amphibian phylogenetic relationships**. *Ethol Ecol Evol* **31**, 526-543. https://doi.org/10.1080/03949370.2019.1630012

Caorsi V, Guerra V, Furtado R et al. (2019) **Anthropogenic substrate-borne vibrations impact anuran calling**. *Sci Rep* **9**, 19456. https://doi.org/10.1038/s41598-019-55639-0

Cardillo M (2021) **Clarifying the relationship between body size and extinction risk in amphibians by complete mapping of model space**. *Proc Biol Sci* **288**, 20203011. https://doi.org/10.1098/rspb.2020.3011

Chan HK, Shoemaker KT, Karraker NE (2014) **Demography of *Quasipaa* frogs in China reveals high vulnerability to widespread harvest pressure**. *Biol Conserv* 170, 3-9. https://doi.org/10.1016/j.biocon.2013.12.014

Chen C, Chen C, Wang Y (2019) **Ecological correlates of extinction risk in Chinese amphibians**. *Divers Distrib* **25**, 1586-1598. https://doi.org/10.1111/ddi.12961

Chichorro F, Juslén A, Cardoso P (2019) **A review of the relation between species traits and extinction risk**. *Biol Conserv* **237**, 220-229. https://doi.org/10.1016/j.biocon.2019.07.001

Chichorro F, Urbano F, Teixeira D et al. (2022) **Trait-based prediction of extinction risk across terrestrial taxa**. *Biol Conserv* **274**, 109738. https://doi.org/10.1016/j.biocon.2022.109738

Cooper N, Bielby J, Thomas GH et al. (2008) **Macroecology and extinction risk correlates of frogs**. *Glob Ecol Biogeogr* **17**, 211-221. https://doi.org/10.1111/j.1466-8238.2007.00355.x

Cowie RH, Bouchet P, Fontaine B (2022) **The sixth mass extinction: fact, fiction or speculation?** *Biol Rev* **97**, 640-663. https://doi.org/10.1111/brv.12816

Duellman WE, Trueb L (1986) **Biology of amphibians**. McGraw-Hill, New York.

Faria RR, Luiz RP, Marcio FS et al. (2021) **The Haeckelian shortfall or the tale of the missing semaphoronts**. *J Zoo Syst Evol Research* **59**, 359-369. https://doi.org/10.1111/jzs.12435

Fei L (2020) **Atlas of amphibians in China (Field edition)**. Henan Science and Technology Press, Henan.

Fei L, Hu S, Ye C (2009a) **Fauna Sinica Amphibia. Vol.2. Anura**. Science Press, Beijing.

Fei L, Hu S, Ye C (2009b) **Fauna Sinica Amphibia. Vol.3. Anura Ranidae**. Science Press, Beijing.

Frost, Darrel R (2026) **Amphibian species of the world: an online reference. Version 6.2.** https://amphibiansoftheworld.amnh.org/index.php accessed: January 10, 2026.

Goedert D, Calsbeek R (2019) **Experimental evidence that metamorphosis alleviates genomic conflict**. *Am Nat* **194**, 356-366. https://doi.org/10.1086/704183

González-del-Pliego P, Freckleton RP, Edwards DP et al. (2019) **Phylogenetic and trait-based prediction of extinction risk for Data-Deficient amphibians.** *Curr Biol* **29**, 1557-1563. https://doi.org/10.1016/j.cub.2019.04.005

Grenat P, Ferrero M, Baraquet M et al. (2024) **Changes in call properties of *Boana pulchella* (Anura, Hylidae) in response to different noise conditions**. *Curr Zool* **70**, 548-556. https://doi.org/10.1093/cz/zoad040

Grenat PR, Pollo FE, Ferrero MA et al. (2019) **Differential and additive effects of natural biotic and anthropogenic noise on call properties of *Odontophrynus americanus* (Anura, Odontophryinidae): Implications for the conservation of anurans inhabiting noisy environments**. *Ecol Indic* **99**, 67-73. https://doi.org/10.1016/j.ecolind.2018.12.014

Haas A, Das I, Hertwig ST et al. (2022) **A Guide to the Tadpoles of Borneo**. Tredition GmbH, Germany.

Hamer AJ, Parris KM (2011) **Local and landscape determinants of amphibian communities in urban ponds**. *Ecol Appl* **21**, 378-390. https://doi.org/10.1890/10-0390.1

Holzer KA (2014) **Amphibian use of constructed and remnant wetlands in an urban landscape**. *Urban Ecosyst* **17**, 955-968. https://doi.org/10.1007/s11252-014-0373-0

Huang CH, Zhong MJ, Liao WB et al. (2019) **Investigating the role of body size, ecology, and behavior in anuran eye size evolution**. *Evol Ecol* **33**, 585-598. https://doi.org/10.1007/s10682-019-09993-0

Huang N, Sun XY, Song YF et al. (2023) **Amphibian traits database: A global database on morphological traits of amphibians**. *Glob Ecol Biogeogr* **32**, 633-641. https://doi.org/10.1111/geb.13656

IUCN (2025) **The IUCN Red List of Threatened Species Version 2025-2**. https://www.iucnredlist.org accessed: January 2, 2026.

Jennings R, Scott Jr N (1993) **Ecologically correlated morphological variation in tadpoles of the leopard frog, *Rana chiricahuensis***. *J Herpetol* **27,** 285-293. https://doi.org/10.2307/1565149

Keane A, Brooke MdL, McGowan PJK (2005) **Correlates of extinction risk and hunting pressure in gamebirds (Galliformes)**. *Biol Conserv* **126**, 216-233. https://doi.org/10.1016/j.biocon.2005.05.011

Keck F, Peller T, Alther R et al. (2025) **The global human impact on biodiversity**. *Nature* **641**, 395-400. https://doi.org/10.1038/s41586-025-08752-2

Laudor J, Schulze A, Veith M et al. (2021) **Morphology of lentic and lotic tadpoles from Madagascar**. *BMC Zool* **6,** 28-. https://doi.org/10.1186/s40850-021-00091-9

Lescano J, Miloch D, Leynaud G (2018) **Functional traits reveal environmental constraints on amphibian community assembly in a subtropical dry forest**. *Austral Ecol* **43**, 623-634. https://doi.org/10.1111/aec.12607

Liu X, Li S, Feng Y et al. (2024) **Traditional knowledge of animal-derived medicines used by Gelao community in Northern Guizhou, China**. *J Ethnobiol Ethnomed* **20**, 31. https://doi.org/10.1186/s13002-024-00669-w

Luo C, Zhao W, Liu S et al. (2023) **Animal-and mineral-based medicines in Gansu-Ningxia-inner Mongolia region, P.R. China: a cross-cultural ethnobiological assessment**. *Front Pharmacol* **14**, 1295806. https://doi.org/10.3389/fphar.2023.1295806

McDiarmid RW, Altig R (1999) **Tadpoles: the biology of anuran larvae**. University of Chicago Press, Chicago.

MEP (The Ministry of Environment Protection), CAS (The Chinese Academy of Sciences) (2023) **Red List of China's Biodiversity Vertebrate Volume (2020)**.

https://www.mee.gov.cn/xxgk2018/xxgk/xxgk01/202305/W020230522536559098623.pdf accessed: January 2, 2026.

Moran, Nancy A (1994) **Adaptation and constraint in the complex life cycles of animals**. *Annu Rev Ecol Syst* **25**, 573-600. https://doi.org/10.1146/annurev.es.25.110194.003041

Ning L, Yu S, Wang P et al. (2025) **Climate change risk to giant panda populations: Insights from changes in both habitat area and bioclimatic velocity**. *Glob Chang Biol* **31**, e70442. https://doi.org/10.1111/gcb.70442

Nolan N, Hayward MW, Klop-Toker K et al. (2023) **Complex organisms must deal with complex threats: How does amphibian conservation deal with biphasic life cycles?** *Animals* **13**, 1634. https://doi.org/10.3390/ani13101634

Nolte D, Boutaud E, Kotze DJ et al. (2019) **Habitat specialization, distribution range size and body size drive extinction risk in carabid beetles**. *Biodivers Conserv* **28**, 1267-1283. https://doi.org/10.1007/s10531-019-01724-9

Nori J, Baldo D, Pereyra M et al. (2025) **Global key areas for anuran tadpole discovery**. *Biol J Linn Soc* **145**, blaf017. https://doi.org/10.1093/biolinnean/blaf017

Owens IP, Bennett PM (2000) **Ecological basis of extinction risk in birds: habitat loss versus human persecution and introduced predators**. *Proc Natl Acad Sci U S A* **97**, 12144-12148. https://doi.org/10.1073/pnas.200223397

Paluh DJ, Stanley EL, Blackburn DC (2020) **Evolution of hyperossification expands skull diversity in frogs**. *Proc Natl Acad Sci U S A* **117**, 8554-8562. https://doi.org/10.1073/pnas.2000872117

Paradis E, Schliep K (2018) **ape 5.0: an environment for modern phylogenetics and evolutionary analyses in R**. *Bioinformatics* **35**, 526-528. https://doi.org/10.1093/bioinformatics/bty633

Penone C, Davidson AD, Shoemaker KT et al. (2014) **Imputation of missing data in life-history trait datasets: which approach performs the best?** *Methods Ecol Evol* **5**, 961-970. https://doi.org/10.1111/2041-210X.12232

Pereyra MO, Womack MC, Barrionuevo JS et al. (2016) **The complex evolutionary history of the tympanic middle ear in frogs and toads (Anura)**. *Sci Rep* **6,** 34130. https://doi.org/10.1038/srep34130

Phillips PC (1998) **Genetic constraints at the metamorphic boundary: Morphological development in the wood frog, *Rana sylvatica***. Journal of Evolutionary Biology **11**, 453-463. https://doi.org/10.1046/j.1420-9101.1998.11040453.x

Phung TX, Nascimento JCS, Novarro AJ et al. (2020) **Correlated and decoupled evolution of adult and larval body size in frogs**. *Proc Biol Sci* **287**, 20201474. https://doi.org/10.1098/rspb.2020.1474

Pinheiro J, Bates D, R Core Team (2025) **nlme: Linear and Nonlinear Mixed Effects Models**.

Pitogo KME, Saavedra AJL, Aurellado MEB et al. (2021) **Functional traits and environment drive montane amphibian distribution in the southern Philippines**. *Biodivers Conserv* **30,** 4177-4197. https://doi.org/10.1007/s10531-021-02299-0

Purvis A, Gittleman JL, Cowlishaw G et al. (2000) **Predicting extinction risk in declining species**. *Proc R Soc Lond B* **267**, 1947-1952. https://doi.org/10.1098/rspb.2000.1234

R Core Team (2024) R: A language and environment for statistical computing. (R foundation for statistical computing, Vienna, Austria).

Revell LJ, Harmon LJ (2022) **Phylogenetic comparative methods in R**. Princeton University Press, Princeton

Roehrdanz PR (2026) **Beyond species ranges: How functional diversity and integrated life history can inform conservation priorities**. *Proc Natl Acad Sci U S A* **123**, e2531790123. https://doi.org/doi:10.1073/pnas.2531790123

Ruland F, Jeschke JM (2017) **Threat-dependent traits of endangered frogs**. *Biol Conserv* **206**, 310-313. https://doi.org/10.1016/j.biocon.2016.11.027

Schwartz JJ, Buchanan BW, Gerhardt HC (2001) **Female mate choice in the gray treefrog (*Hyla versicolor*) in three experimental environments**. *Behav Ecol Sociobiol* 49, 443-455. https://doi.org/10.1007/s002650100317

Seibold S, Brandl R, Buse J et al. (2015) **Association of extinction risk of saproxylic beetles with ecological degradation of forests in Europe**. *Conserv Biol* **29**, 382-390. https://doi.org/10.1111/cobi.12427

Sherratt E, Vidal-García M, Anstis M et al. (2017) **Adult frogs and tadpoles have different macroevolutionary patterns across the Australian continent**. *Nat Ecol Evol* **1**, 1385-1391. https://doi.org/10.1038/s41559-017-0268-6

Song YF, Liu XL, Liu JJ et al. (2025a) **Biodiversity conservation requires consideration of different life history stages**. *Proc Natl Acad Sci U S A* **122**, e2507870122. https://doi.org/10.1073/pnas.2507870122

Song YF, Tian R, Wang YL et al. (2025b) **TadpoleTraits: A Global Database on Morphological Traits of Tadpoles of Anura**. *Glob Ecol Biogeogr* **34**, e70055. https://doi.org/10.1111/geb.70055

Stekhoven DJ (2022) **missForest: Nonparametric missing value imputation using random forest**. In: R package version15.

Stekhoven DJ, Bühlmann P (2011) **MissForest—non-parametric missing value imputation for mixed-type data**. *Bioinformatics* **28**, 112-118. https://doi.org/10.1093/bioinformatics/btr597

Sun Z, Zhao C, Zhu W et al. (2021) **Microhabitat features determine the tadpole diversity in mountainous streams**. *Ecol Indic* **126,** 107647. https://doi.org/10.1016/j.ecolind.2021.107647

Swenson NG (2014) **Functional and phylogenetic ecology in R (Vol. 639)**. Springer, New York.

Terzopoulou S, Rigal F, Whittaker RJ et al. (2015) **Drivers of extinction: the case of Azorean beetles**. *Biol Lett* **11**, 20150273. https://doi.org/10.1098/rsbl.2015.0273

Tian YB, Xia MM, Shao C (2011) **Advances in germplasm resource research of *Hoplobatrachus chinensis***. *Journal of Zhejiang Normal University* **34**, 464-468.

Tobias JA, Sheard C, Pigot AL et al. (2022) **AVONET: morphological, ecological and geographical data for all birds**. *Ecol Lett* **25**, 581-597. https://doi.org/https://doi.org/10.1111/ele.13898

Thomas KN, Gower DJ, Bell RC et al. (2020) **Eye size and investment in frogs and toads correlate with adult habitat, activity pattern and breeding ecology**. *Proc Biol Sci* **287,** 20201393. https://doi.org/10.1098/rspb.2020.1393

Tomiya S (2013) **Body size and extinction risk in terrestrial mammals above the species level**. *Am Nat* **182**, E196-E214. https://doi.org/10.1086/673489

Uetz P, Freed P, Aguilar R et al. (2025) **The Reptile Database**. http://www.reptile-database.org accessed: January 10, 2026.

Verde Arregoitia LD (2016) **Biases, gaps, and opportunities in mammalian extinction risk research**. *Mamm Rev* **46**, 17-29. https://doi.org/https://doi.org/10.1111/mam.12049

Vilela B, Villalobos F, Rodríguez MÁ et al. (2014) **Body size, extinction risk and knowledge bias in New World snakes**. *PLOS ONE* **9**, e113429. https://doi.org/10.1371/journal.pone.0113429

Violle C, Navas ML, Vile D et al. (2007) **Let the concept of trait be functional**! *Oikos* **116**, 882-892. https://doi.org/10.1111/j.2007.0030-1299.15559.x

Wei PF, Luo X, Pie MR et al. (2025) **Global diversity patterns in anurans are determined by terrestrial and arboreal species**. *Integr Zool* **0**: 1-9. https://doi.org/10.1111/1749-4877.13032

Wells KD (2019) **The ecology and behavior of amphibians**. University of Chicago press, Chicago.

Werner E (1988) **Size, scaling, and the evolution of complex life cycles**. Size-structured populations: ecology and evolution, 60-81.

Wilczynski W, Capranica RR (1984) **The auditory system of anuran amphibians**. *Prog Neurobiol* **22,** 1-38. https://doi.org/10.1016/0301-0082(84)90016-9

Wollenberg Valero KC, Garcia-Porta J, Rodríguez A et al. (2017) **Transcriptomic and macroevolutionary evidence for phenotypic uncoupling between frog life history phases**. *Nat Commun* **8**, 15213. https://doi.org/10.1038/ncomms15213

Womersley FC, Sousa LL, Humphries NE et al. (2024) **Climate-driven global redistribution of an ocean giant predicts increased threat from shipping**. Nature Climate Change **14**, 1282-1291. https://doi.org/10.1038/s41558-024-02129-5

Xu W, Wu YH, Zhou WW et al. (2024) **Hidden hotspots of amphibian biodiversity in China**. *Proc Natl Acad Sci U S A* **121**, e2320674121. https://doi.org/10.1073/pnas.2320674121

Zhao L, Deng K, Wang T et al. (2025a) **Anuran communities increase aggregations of conspecific calls in response to aircraft noise**. *Curr Zool* **71**, 223-232. https://doi.org/10.1093/cz/zoae042

Zhao LX, Li RQ, Xiao ZJ (2014) **Research status on the development and utilization of *Rana dybowskii***. *Journal of Veterinary Science and Technology Information* **4**, 4-5.

Zhao Y, Liu J, Wang F et al. (2025b) **Targeted conservation actions are required to save species from extinction**. *Biol Conserv* **310**, 111340. https://doi.org/https://doi.org/10.1016/j.biocon.2025.111340

Figure 1. Distribution of threat status across anuran families in China, based on the China Biodiversity Red List – Vertebrates Volume (2020). Each stacked bar represents the proportion of species within a family categorized as Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), or Least Concern (LC). Families are ordered by total number of species.

Figure 2. Phylogenetically corrected associations between functional traits and extinction risk in Chinese anurans, separately for (A) adults and (B) tadpoles. Each dot represents the PGLS regression coefficient (β) for a given trait, with horizontal lines indicating 95% confidence intervals. Traits significantly associated with threat status are marked with asterisks (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$). For abbreviations of traits, please refer to Table 1. The silhouette images are sourced from https://www.phylopic.org/images.

Table 1. Functional traits and its potential ecological functions.

Table 2. Regression analysis results of extinction risk for adult and tadpole stages. For abbreviations of traits, please refer to Table 1.

Table 3. Relationships between tadpole and adult size within anuran families. SVL: snout-vent length; TOL: total length.

Table 1: Functional traits and its potential ecological functions.

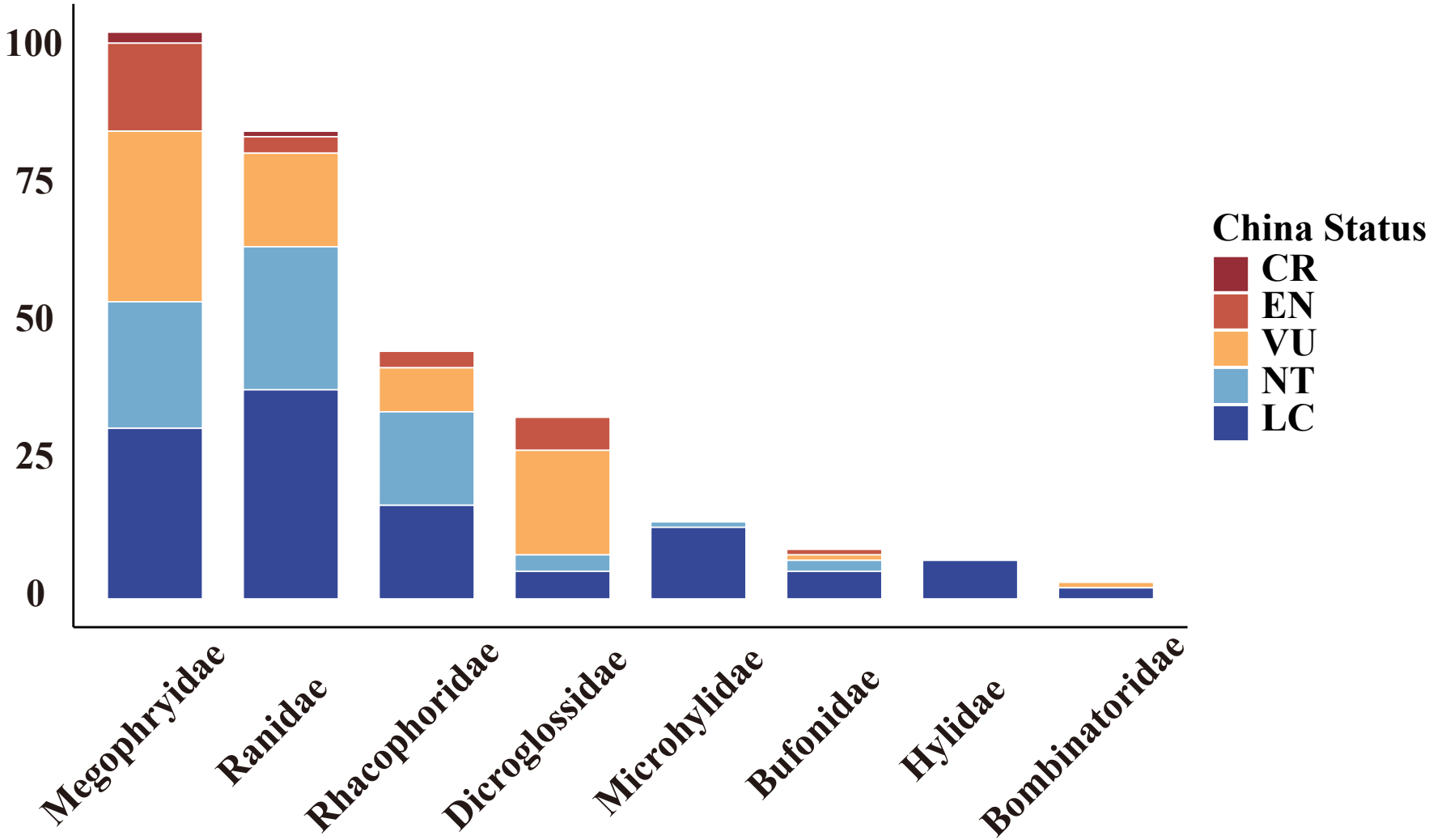
Life stage	Functional trait	Trait abbreviation	Description	Ecological relevance	Reference
Adult	Snout-vent length	SVL	Distance from tip of snout to posterior margin of vent	Body size. Resource acquisition	(Lescano et al., 2018; Campos et al., 2019; Wells, 2019; Pitogo et al., 2021)
	Head length	HL	Distance from the posterior of the jaws to the tip of the snout	Resource use and acquisition	(Fei, 2009; Lescano et al., 2018; Pitogo et al., 2021)
	Head width	HW	The maximum distance between the sides of the head		
	Eye diameter	ED	The horizontal distance from the anterior to posterior corner of the eye	Predation and anti-predator capabilities	(Wilczynski & Capranica, 1984; Pereyra et al., 2016; Huang et al., 2019; Thomas et al., 2020)
	Tympanum diameter	TD	Greatest horizontal width of the tympanum		
	Hand length	HAL	Distance from the base of the outer palmar tubercle to the tip of Finger III	Resource use. Locomotor ability and modes of locomotion	(Fei, 2009; Lescano et al., 2018; Pitogo et al., 2021)
	Foot length	FL	Distance from the base of the inner metatarsal tubercle to the tip of Toe IV		
	Tibia length	TL	Distance from the outer surface of the flexed knee to the heel/tibiotarsal inflection		
	Arboreal	Arboreal	0: presence; 1: absence	Habitat use	(Duellman & Trueb, 1986; McDiarmid & Altig, 1999; Fei, 2009)
	Fossorial	Fossorial	0: presence; 1: absence		
	Terrestrial	Terrestrial	0: presence; 1: absence		
	Aquatic	Aquatic	0: presence; 1: absence		
	Torrential	Torrential	0: presence; 1: absence		
Tadpole	Total length	TOL	Length from snout to end of tail	Body size. Resource acquisition	(Altig & Johnston, 1989; McDiarmid & Altig, 1999; Baldo et al., 2014; Laudor et al., 2021)
	body length	BL	Length from snout to vent tube	Position in the water column and hydrodynamism	(McDiarmid & Altig, 1999; Baldo et al., 2014; Sun et al., 2021)
	Body width	BW	The maximum width on both sides of the body		
	Body height	BH	Maximum height between dorsal and ventral surfaces		
	Tail length	TL	Length from base to end of tail	Swimming ability and maneuverability	(Jennings & Scott Jr, 1993; McDiarmid & Altig, 1999; Sun et al., 2021)
	Tail height	TH	Maximum height between upper and lower fins edges		
	Tail muscle height	TMH	The height of the tail muscles		
	Oral disc width	ODW	The maximum width of the oral disc	The ability to exploit food resources	(Altig & Johnston, 1989; McDiarmid & Altig, 1999; Sun et al., 2021),
	Lentic	Lentic	0: presence; 1: absence	Habitat use	(McDiarmid & Altig, 1999; Fei, 2009; Laudor et al., 2021)
	Lotic	Lotic	0: presence; 1: absence		

Table 2. Regression analysis results of extinction risk for adult and tadpole stages. For abbreviations of traits, please refer to Table 1.

Life stage	**Model type**	**AIC**	**Model**
Adult	PGLS_BM	1026.66	/
	PGLS_OU	858.02	China extinction risk ~ 0.52 SVL** + 6.86 HL*** - 0.86 HW + 4.30 ED - 5.91 TD* - 2.06 HAL - 0.68 FL + 0.17 TL - 0.07 Arboreal - 0.13 Fossorial + 0.28 Terrestrial + 0.07 Aquatic - 0.17 Torrential
	GLS_no_phylogeny	860.20	/
Tadpole	PGLS_BM	1031.47	/
	PGLS_OU	872.76	China extinction risk ~ 0.40 TOL* + 2.69 BL - 3.58 BW + 3.96 BH + 0.20 TL + 1.00 TH - 2.73 TMW + 2.88 MW - 0.55 Lentic* + 0.06 Lotic
	GLS_no_phylogeny	875.83	/

Table 3. Relationships between tadpole and adult size within anuran families. SVL: snout-vent length; TOL: total length..

Family	**Coefficient**	**Phylogenetic signal of SVL**	**Phylogenetic signal of TOL**
All	0.12	0.58	0.13
Bufonidae	0.11	0.00	2.74
Dicroglossidae	0.30	0.79	0.06
Hylidae	-0.12	0.22	1.47
Megophryidae	0.33	0.67	0.09
Microhylidae	0.37	1.93	0.53
Ranidae	0.34	0.00	0.00
Rhacophoridae	0.24	0.50	0.55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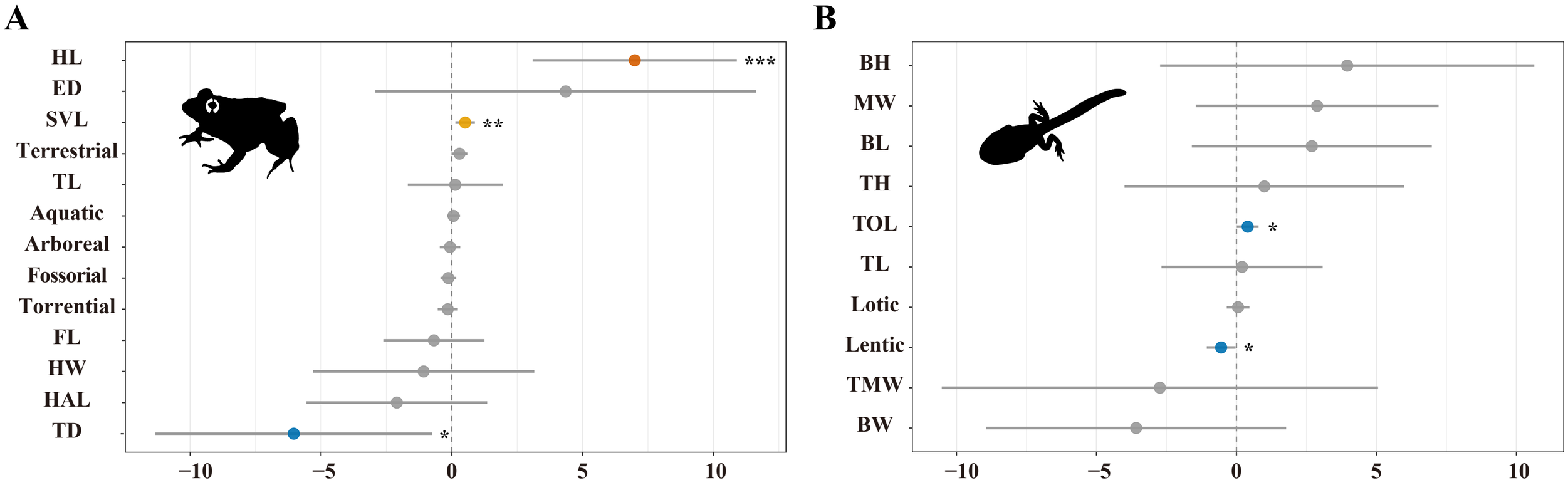
Megophryidae
Ranidae
Rhacophoridae
Dicroglossidae
Microhylidae
Bufonidae
Hylidae
Bombinatoridae
China Status
CR
EN
VU
NT
LC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