Received: 23 December 2023 | Revised: 17 April 2024 | Accepted: 26 April 2024

DOI: 10.1111/gcb.17318

Global Change Biology WILEY

RESEARCH ARTICLE

Acclimation capacity to global warming of amphibians and freshwater fishes: Drivers, patterns, and data limitations

Katharina Ruthsatz[1,2] | Flemming Dahlke[3] | Katharina Alter[4] | Sylke Wohlrab[5,6] | Paula C. Eterovick[1] | Mariana L. Lyra[7,8] | Sven Gippner[1] | Steven J. Cooke[9] | Myron A. Peck[4,10]

[1]Zoological Institute, Technische Universität Braunschweig, Braunschweig, Germany

[2]Institute of Animal Cell and Systems Biology, Universität Hamburg, Hamburg, Germany

[3]Ecology of Living Marine Resources, Universität Hamburg, Hamburg, Germany

[4]Department of Coastal Systems, Royal Netherlands Institute for Sea Research, Den Burg, The Netherlands

[5]Alfred Wegner Institute Helmholtz Center for Polar and Marine Research, Bremerhaven, Germany

[6]Helmholtz Institute for Functional Marine Biodiversity at the University of Oldenburg (HIFMB), Oldenburg, Germany

[7]New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

[8]Center for Research on Biodiversity Dynamics and Climate Change, State University of São Paulo-UNESP, Rio Claro, Brazil

[9]Fish Ecology and Conservation Physiology Laboratory, Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, Ottawa, Ontario, Canada

[10]Marine Animal Ecology Group, Department of Animal Sciences, Wageningen University, Wageningen, The Netherlands

Correspondence
Katharina Ruthsatz, Zoological Institute, Technische Universität Braunschweig, Mendelssohnstraße 4, 38106 Braunschweig, Germany.
Email: katharinaruthsatz@gmail.com

Funding information
Deutsche Forschungsgemeinschaft, Grant/Award Number: 459850971; São Paulo Research Foundation, Grant/Award Number: 2021/10639-5; University of Hamburg

Abstract

Amphibians and fishes play a central role in shaping the structure and function of freshwater environments. These organisms have a limited capacity to disperse across different habitats and the thermal buffer offered by freshwater systems is small. Understanding determinants and patterns of their physiological sensitivity across life history is, therefore, imperative to predicting the impacts of climate change in freshwater systems. Based on a systematic literature review including 345 experiments with 998 estimates on 96 amphibian (Anura/Caudata) and 93 freshwater fish species (Teleostei), we conducted a quantitative synthesis to explore phylogenetic, ontogenetic, and biogeographic (thermal adaptation) patterns in upper thermal tolerance (CT_{max}) and thermal acclimation capacity (acclimation response ratio, ARR) as well as the influence of the methodology used to assess these thermal traits using a conditional inference tree analysis. We found globally consistent patterns in CT_{max} and ARR, with phylogeny (taxa/order), experimental methodology, climatic origin, and life stage as significant determinants of thermal traits. The analysis demonstrated that CT_{max} does not primarily depend on the climatic origin but on experimental acclimation temperature and duration, and life stage. Higher acclimation temperatures and longer acclimation times led to higher CT_{max} values, whereby Anuran larvae revealed a higher CT_{max} than older life stages. The ARR of freshwater fishes was more than twice

that of amphibians. Differences in ARR between life stages were not significant. In addition to phylogenetic differences, we found that ARR also depended on acclimation duration, ramping rate, and adaptation to local temperature variability. However, the amount of data on early life stages is too small, methodologically inconsistent, and phylogenetically unbalanced to identify potential life cycle bottlenecks in thermal traits. We, therefore, propose methods to improve the robustness and comparability of CT_{max}/ARR data across species and life stages, which is crucial for the conservation of freshwater biodiversity under climate change.

KEYWORDS
acclimation response ratio, Bogert effect, climate variability hypothesis, CT_{max}, developmental phenotypic plasticity, metamorphosis, thermal bottleneck, thermal tolerance plasticity

1 | INTRODUCTION

Global climate change is not only causing an increase in mean air and water temperatures, but also an increased magnitude and frequency of extreme climatic events (Lee et al., 2023). As a result, ectotherms are more likely to experience temperatures beyond their critical thermal maximum (CT_{max}) in both terrestrial and aquatic habitats (Duarte et al., 2012; Sunday et al., 2014). This is particularly true for populations already living close to their upper thermal limit. Consequently, the ability to mitigate thermal stress through either migration, evolutionary genetic adaptation or acclimation is crucial for the persistence of species in a changing climate (Franks & Hoffmann, 2012; Huey et al., 2012; Seebacher et al., 2015). Given the limited dispersal ability of many species (e.g., freshwater species; Woodward et al., 2010) and rapid pace of global warming (Hoffmann & Sgró, 2011), physiological acclimation is arguably the most important mechanism for coping with climate change (Gunderson & Leal, 2016). Understanding differences in acclimation capacity of species and identifying global patterns can, therefore, help to identify climate change risks to biodiversity and develop effective conservation measures (Somero, 2010).

As an adaptive response to larger seasonal differences in temperature, thermal tolerance and acclimation capacity of ectothermic species or populations tend to increase with increasing latitude from tropical through temperate climate zones (e.g., Cicchino et al., 2023; Deutsch et al., 2008; Peck et al., 2014; Rohr et al., 2018; Somero, 2005; Sunday et al., 2011; but see: Gunderson & Stillman, 2015; Sørensen et al., 2016) and from higher to lower elevations (Enriquez-Urzelai et al., 2020; but not: Gutiérrez-Pesquera et al., 2022; Sunday et al., 2019). This biogeographical pattern is consistent with the *climate variability hypothesis* (Ghalambor et al., 2006; Janzen, 1967), suggesting that climatic differences across altitudinal and latitudinal gradients lead to corresponding adaptations in thermal physiology (but see: Gutiérrez-Pesquera et al., 2022). Low-latitude species adapted to relatively stable temperature conditions may have a lower acclimation capacity and, therefore, may be more vulnerable to climate change (Sunday et al., 2014; Tewksbury et al., 2008; but see: Bovo et al., 2023). However, there is still little empirical evidence supporting the climate variability hypothesis, possibly due to the limited geographical and phylogenetic coverage of observations, and because of the inconsistency of the methods applied to measure the acclimation capacity of different species and life stages (Gutiérrez-Pesquera et al., 2016; Shah et al., 2017). Moreover, the use of different methods or protocols might impact the estimation of thermal traits (Chown et al., 2009; Pottier, Burke, Drobniak, et al., 2022; Rohr et al., 2018; Terblanche et al., 2007; but not: Sunday et al., 2019). For example, acclimation duration (i.e., how long organisms were held at an acclimation temperature before being exposed to the test temperature; Rohr et al., 2018; Ruthsatz, Dausmann, et al., 2022) and ramping protocol (i.e., heating or cooling rate in thermal tolerance trials; Illing et al., 2020; Penman et al., 2023) have been suggested to influence measurements of acclimation capacity, as the underlying physiological processes occur over certain time periods.

In animals with complex life histories, thermal tolerance and acclimation capacity are thought to change during ontogeny according to physiological and morphological reorganizations and concomitant aerobic capacities in relation to oxygen demand (Pörtner, 2002; Pörtner & Peck, 2010; Ruthsatz, Dausmann, et al., 2022; Ruthsatz, Dausmann, Paesler, et al., 2020; Ruthsatz, Dausmann, Reinhardt, et al., 2020) as well as energetic costs associated with developmental processes (Ruthsatz et al., 2019). Furthermore, life stages might differ in their ability for behavioral thermoregulation (Little & Seebacher, 2017; Navas et al., 2008) resulting in stage-specific adaptations in thermal traits (Huey et al., 1999). Therefore, determining taxon-specific acclimation capacity at different ontogenetic stages should be taken into account when studying climate adaptation of ectothermic species, as it will help identify life cycle bottlenecks and provide robust data on the vulnerability of populations or species to global warming (Bodensteiner et al., 2021; Dahlke et al., 2022; Pottier, Burke, Drobniak, et al., 2022). To date, most studies have not distinguished among life stages or have only focused on adults when addressing the *climate variability hypothesis* (e.g., Gunderson & Stillman, 2015; Rohr et al., 2018; Sunday et al., 2011, 2014, 2019) and the vulnerability of species to global change (e.g., Calosi et al., 2008; Comte & Olden, 2017a; Molina et al., 2023; Morley

et al., 2019). Moreover, most studies have pooled several pre- and post-metamorphic life stages (Pottier, Burke, Drobniak, et al., 2022; Weaving et al., 2022) thereby risking to overlook a critical thermal bottleneck in the life cycle (Dahlke et al., 2020). The extent to which thermal tolerance and acclimation capacity change during ontogeny is, therefore, not clear for many taxa.

Amphibians and freshwater fishes tend to live in relatively shallow waters (e.g., wetlands, ponds, rivers, lakes) and may, therefore, experience strong seasonal and daily temperature fluctuations (Capon et al., 2021) and climate extremes such as heat waves (IPCC, 2021). In addition, both taxa have a limited ability to disperse over larger distances and habitats to avoid unfavorable climatic conditions (Albert et al., 2011; Campos et al., 2021; Yu et al., 2013). Consequently, as a result of local adaptation (Meek et al., 2023), there should be a close correspondence between the capacity for thermal acclimation and the climatic conditions that amphibians and freshwater fishes experience during their life cycle. However, freshwater systems offer a wide range of thermal microhabitats that enable behavioral thermoregulation (Campos et al., 2021), especially for (post-metamorphic) amphibians that can switch between water and land. The potential of behavioral thermoregulation could reduce the need for physiological adaptations (also known as the *Bogert Effect*, Bogert, 1949) and thus counteract the emergence of geographical patterns in thermal acclimation capacity and/or thermal tolerance. Given the central role that amphibians and freshwater fishes play in shaping the structure and function of these ecosystems (Closs et al., 2016; Hocking & Babbitt, 2014), understanding determinants and patterns of their physiological sensitivity is imperative to predicting the impacts of climate change on freshwater systems.

Here, we aimed to define the determinants and patterns of acclimation capacity in upper thermal tolerance in amphibians and freshwater fishes addressing, for the first time, ontogeny dependent variation. To do so, we compiled literature on upper thermal tolerance and collected empirical data for CT_{max} in four amphibian (i.e., larvae, metamorphs, juveniles, and adults) and three freshwater fish (i.e., larvae, juveniles, and adults) life stages acclimated to at least two different temperatures. Next, we calculated the population-specific acclimation capacity, that is, mean acclimation response ratio (ARR) of upper thermal limits (i.e., the slope of the linear function describing the change in thermal tolerance with a given change in acclimation temperature; e.g., Claussen, 1977; Hutchison, 1961), and conducted a quantitative synthesis on the acclimation capacity of amphibians and freshwater fishes to test for differences among taxonomic groups, among life stages, and across thermal characteristics of populations, that is, biogeographic differences based on local thermal adaptation. Further, we investigated how the methodological context (i.e., acclimation duration and temperature, ramping rate) affects estimates of thermal traits. Finally, we summarize methodological concerns, highlight key knowledge gaps, and provide research recommendations for generating reliable and comparable data on the acclimation capacity of ectothermic species and their life stages. This will improve our ability to predict future climate vulnerability of species and populations.

2 | MATERIALS AND METHODS

2.1 | Systematic literature review

We conducted a systematic literature review using ISI Web of Science (ISI WOS, 2021) on 2022/06/30 and did not apply a timespan limit. The following Boolean search string was used to capture articles with experimental studies manipulating acclimation temperatures of amphibians and freshwater fishes at different life stages, and subsequently measured their CT_{max}: ("amphibian*" OR "newt*" OR "frog*" OR "toad*" OR "salamander*" OR "freshwater" AND "fish*") AND ("early" OR "young" OR "life stage*" OR "ontogen*" OR "development*" OR "hatchling*" OR "alevin*" OR "larv*" OR "tadpole*" OR "metamorph*" OR "postmetamorph*" OR "post-metamorph*" OR "postlarva*" OR "post-larva*" OR "fry*" OR "parr*" OR "smolt*" OR "subadult*" OR "sub-adult" OR "juvenile" OR "fingerling*" OR "adult*") AND ("thermal" OR "temperature" OR "acclimat*" OR "heat" OR "warm*") AND ("tolerance*" OR "thermal tolerance*" OR "temperature tolerance*" OR "warming tolerance*" OR "heat tolerance*" OR "thermal stress tolerance*" OR "heat stress tolerance*" OR "temperature stress tolerance*" OR "limit*" OR "temperature stress*" OR "thermal limit*" OR "critical temperature*" OR "CT max" OR "critical thermal m*" OR "thermal performance breadth*" OR "thermal breadth*" OR "performance breadth*" OR "thermal range*" OR "thermal window*" OR "thermal tolerance window*" OR "tolerance window*" OR "sensitivity*" OR "thermal sensitivity").

Our search resulted in 11,057 documents (Figure S1). After removing book chapters, conference contributions, reviews, meeting abstracts, editorial material, preprints, and proceedings articles, 10,740 published peer-reviewed articles remained in our initial database. Additionally, we manually added articles included in the meta-analyses of Claussen (1977), Gunderson and Stillman (2015), Comte and Olden (2017b), Morley et al. (2019) and Dahlke et al. (2020) that met our inclusion criteria (specified below) but were not obtained through the ISI Web of Science search. After an initial subjective evaluation of titles, 3991 articles potentially containing results matching the objective of the present study were kept and further assessed for eligibility using the abstract. Thirty-four articles were not accessible. We contacted the authors of the original articles to request missing information and heard back from two authors. Finally, a total of 91 articles (33 on amphibians; 58 on freshwater fishes) met our inclusion criteria. Search methods are summarized in a PRISMA flowchart (Figure S1), and a list of included articles and experimental studies therewithin is available in the figshare data repository under https://figshare.com/s/57775032a0b79c416ef2 (https://doi.org/10.6084/m9.figshare.24872133).

2.2 | Inclusion criteria

Experimental studies were selected based on the following seven inclusion criteria:

1. Experimental studies were conducted on amphibians (anurans, caudates, or gymnophiones) or freshwater fishes (teleosts).
2. Animals were acclimated to at least two constant acclimation temperatures under laboratory conditions prior to the CT_{max} measurements. Fluctuating temperature treatments were not considered. Therefore, field experiments were not considered since the acclimation temperature under field conditions is likely to fluctuate.
3. Articles provided comprehensive information on methodology (acclimation temperatures and duration, ramping rate), phylogeny (species names), sampling location (GPS location), and life stage. If no GPS coordinates were provided but a concrete sampling location was stated (e.g., Central Park, New York City, NY, USA), we searched for the coordinates of the respective location on Google Maps.
4. Animals were collected from their natural habitat. Data were excluded if measurements were taken from specimens bred artificially to reduce confounding issues associated with artificial selective history (Bennett et al., 2018). Experimental studies were also included if adult animals were collected to immediately reproduce in the lab to obtain larvae.
5. The critical thermal maximum (CT_{max}) was used as a standard measure of heat tolerance (Lutterschmidt & Hutchison, 1997a). Experimental studies using other measures such as voluntary thermal maximum, time to death, heat knockdown, or lethal temperatures as well as extrapolations from thermal performance curves were not considered. In aquatic and terrestrial ectotherms such as amphibians and fish, CT_{max} is generally measured as loss of equilibrium (LOE) or loss of rightening response (LRR) following a steady increase in water or air temperature (dynamic method according to Fry, 1947). In comparison to other endpoints such as the onset of spasms (Lutterschmidt & Hutchison, 1997b), measuring CT_{max} as LOE or LRR is a non-lethal, robust method at various body sizes that is repeatable within individuals (Morgan et al., 2018).
6. At CT_{max} measurements, the animals could be classified into one of four different categories representing the consecutive life stages of amphibians and freshwater fish: (a) larva (pre-metamorphic; amphibians: <Gosner stage 42), (b) metamorph (only for amphibians: Gosner stage 42–46), (c) juvenile (post-metamorphic), and (d) adult (after reaching sexual maturity). Embryos were not included in the present study because the assessment of acute heat tolerance in non-mobile life stages requires different endpoints that may not be directly comparable to the LOE/LRR-based CT_{max} of other life stages (Cowan et al., 2023; Lechner et al., 2023).
7. Food was provided ad libitum during the acclimation time since food deprivation might decrease thermal tolerance and/or acclimation capacity (Lee et al., 2016).

2.3 | Data extraction

When all inclusion criteria were met, data were collated in a spreadsheet. We extracted mean CT_{max} for all acclimation temperatures resulting in 998 single data points (513 for amphibians; 485 for freshwater fish). Some of the selected articles performed different experimental studies on, for example, different populations of one species, different species, or different life stages. Therefore, all available datasets were included, resulting in 345 experimental studies from 91 articles with 345 paired effect sizes CT_{max} and acclimation capacity. Data presented in the text or tables were directly extracted from the articles. When only raw data were available, mean values were calculated. For articles that presented results in figures instead of tables, Engauge Digitizer 12.1 was used (Mitchell et al., 2021) to extract data from the graphs. In addition to CT_{max} data, information on the methodology (i.e., acclimation temperatures and duration, ramping protocol), as well as on variables representing sampling location as detailed as possible (i.e., GPS coordinates), phylogeny (i.e., scientific classification according to the Linnean classification), and life stage at CT_{max} assessment was extracted. The data extractions were performed by KR, KA and PCE, followed by an accuracy check of the data (KA: freshwater fish sub dataset; KR: amphibian sub dataset; PCE: both sub datasets).

2.4 | Bioclimatic variables

For each sampling location, 19 bioclimatic metrics, related to temperature and precipitation, and elevation were extracted using the WorldClim 2 database (http://www.worldclim.org/; Fick & Hijmans, 2017) for the average of the years 1970–2000. The data were extracted at a spatial resolution of 30 s (~1 km^2), using package "geodata" (Hijmans et al., 2022) in R (version 4.2.1; R Core Team, 2020). Bioclimatic variables are coded as follows (name of the variable and the unit used as input is included in parenthesis): Annual Mean Temperature (Bio1;°C), Mean Diurnal Range (Bio 2;°C), Isothermality (Bio 3; percentage), actual Temperature Seasonality (Bio 4; standard deviation in°C), Maximum Temperature of Warmest Month (Bio 5;°C), Minimum Temperature of Coldest Month (Bio 6;°C), Annual Temperature Range (Bio 7;°C), Mean Temperature of Wettest Quarter (Bio 8;°C), Mean Temperature of Driest Quarter (Bio 9;°C), Mean Temperature of Warmest Quarter (Bio 10;°C), Mean Temperature of Coldest Quarter (Bio 11;°C), Annual Precipitation (Bio 12; mm), Precipitation of Wettest Month (Bio 13; mm), Precipitation of Driest Month (Bio 14; mm), Precipitation Seasonality (Bio 15; coefficient of variation expressed in percent), Precipitation of Wettest Quarter (Bio 16; mm), Precipitation of Driest Quarter (Bio 17; mm), Precipitation of Warmest Quarter (Bio 18; mm), and Precipitation of Coldest Quarter (Bio 19; mm) (http://www.worldclim.org/data/bioclim.html). These macroclimatic data were used as approximations to identify patterns of local adaptation in amphibians and freshwater fish, as microclimatic data (e.g. site-specific temperatures) were not available in original articles or in the WorldClim database. Following

previous studies (Carilo Filho et al., 2022; Morley et al., 2019), mean near-surface air temperature was assumed to reflect the temperature profile of freshwater systems and used to analyze thermal adaptation in both taxa. We are aware that these macroclimatic data as provided by the WorldClim database (representing surface air temperature) present some limitations in reflecting microclimatic data (see Section 5 for methods to improve future studies). In contrast to marine habitats, the temperature of small or shallow bodies of water might fluctuate with the surface air temperature and animals at the surface of freshwater systems might be further exposed to high temperatures. Therefore, we assume that the average near-surface air temperature is a suitable estimate of the temperature of freshwater systems, thereby reflecting the thermal local adaptation of investigated amphibian and freshwater populations. This is in accordance with previous studies testing the effect of thermal adaptation on the thermal physiology of various taxa (e.g., Carilo Filho et al., 2022; Gutiérrez-Pesquera et al., 2016; Morley et al., 2019; Sinai et al., 2022). Sampling locations were assigned to latitudinal groups based on the absolute latitude (°N/S) and were categorized as either tropical (0–25°), subtropical (>25–40°), temperate (>40–53.55°) or polar (>53.55°; Morley et al., 2019).

2.5 | Effect size calculation: ARR

A well-established method to measure acclimation capacity in thermal tolerance in ectothermic animals is the calculation of the ARR, that is, the slope of the linear function describing the change in thermal tolerance with a given change in acclimation temperature (e.g., Claussen, 1977; Gunderson & Stillman, 2015; Hutchison, 1961; Morley et al., 2019). We separately calculated the ARR for CT_{max} within each study using the equation according to Claussen (1977):

$$ARR = \frac{CT_{max_{[T2]}} - CT_{max_{[T1]}}}{T2 - T1},$$

where T represents the acclimation temperature (°C; with $T2$ = highest acclimation temperature and $T1$ = lowest acclimation temperature) and CT_{max} the heat tolerance estimates (°C). When data on more than two acclimation temperatures were presented, we calculated the ARR for each stepwise comparison (e.g., 18–20°C, 20–22°C, 22–24°C; Pottier, Burke, Drobniak, et al., 2022) and used the mean ARR of all comparisons in the statistical analysis. Higher absolute values of ARR correspond to higher plasticity in thermal tolerance limits (i.e., greater acclimation capacity; Claussen, 1977; Gunderson & Stillman, 2015; Kingsolver & Huey, 1998; van Heerwaarden et al., 2016). An ARR of 1.00 indicates a 100% acclimation in thermal tolerance to a temperature increase of 1°C (Morley et al., 2019).

2.6 | Statistical analyses

For all statistical tests R 4.0.2 (R Core Team, 2020) was used. All plots were constructed using R packages "ggplot2" (Wickham & Wickham, 2009), "ggtree" (Yu et al., 2017) and Adobe Illustrator CS6.

Conditional inference tree (CIT) analysis (R package "partykit," Hothorn & Zeileis, 2015) was used to assess the influence of geographic origin (bioclimatic variables, elevation), phylogeny (taxon and order level), experimental methodology (ramping rate, mean acclimation duration, mean acclimation temperature), and ontogeny on CT_{max} and ARR of amphibians and freshwater fishes. As an advantage over traditional (parametric) methods, CIT is a non-parametric method that handles complex non-linear relationships without making specific assumptions about data distribution or being sensitive to outliers. CIT involves recursive partitioning to split data into subsets based on the relevance of predictor variables. At each node of the tree, a permutation-based test (Monte Carlo method with Bonferroni correction) determines whether the split is statistically significant ($\alpha < .05$). The initial split in the tree indicates which predictor variable has the strongest correlation with the response variable (CT_{max} or ARR). The resulting tree provides a hierarchical structure and classification of significant predictor variables. A post-pruning strategy based on the Akaike information criterion (Akaike, 1974) was used to avoid overfitting, that is, removal of nodes that do not improve the overall fit of the model (Hothorn & Zeileis, 2015). The raw data used for the analysis are provided in the electronic Supporting Information (Table S1).

Phylogenetic trees for visualizations were created using the R package "fishtree" (Chang et al., 2019) for freshwater fishes (Teleostei). The amphibian ultrametric tree was obtained from the timetree.org website in June 2022 (Kumar et al., 2022). To ensure the validity, we developed a workflow to filter out taxonomically invalid taxa. Firstly, a time tree was generated using the "Build a Timetree" function on timetree.org. The taxa names were then extracted from the generated time trees using the R package "ape" (Paradis & Schliep, 2019), excluding non-binomial names. The extracted list was cross-checked with the GBIF Backbone Taxonomy using the species matching tool (https://www.gbif.org/tools/species-lookup, accessed June 2022). Matches at the species rank with an accuracy of 100% were extracted and matches with lower accuracy were manually verified. The resulting species list was uploaded back onto timetree.org using the "Load a List of Species" function. The newly generated time tree was then downloaded and used for visualizations.

The relationship between absolute latitude (°N/S), elevation (m), and the bioclimatic variables that revealed a significant effect on CT_{max} (Bio 14, Bio 7) and ARR (Bio 3) in the CIT analysis was assessed using linear regressions. Differences in respective bioclimatic variables between latitudinal groups (tropical, subtropical, temperate, polar) were compared using Kruskal–Wallis tests followed by pairwise Mann–Whitney U- tests with false discovery rate-correction.

We were unable to test for a publication bias (i.e., whether statistically insignificant or negative results are less likely to be published) in our data set given the use of a non-standardized effect size

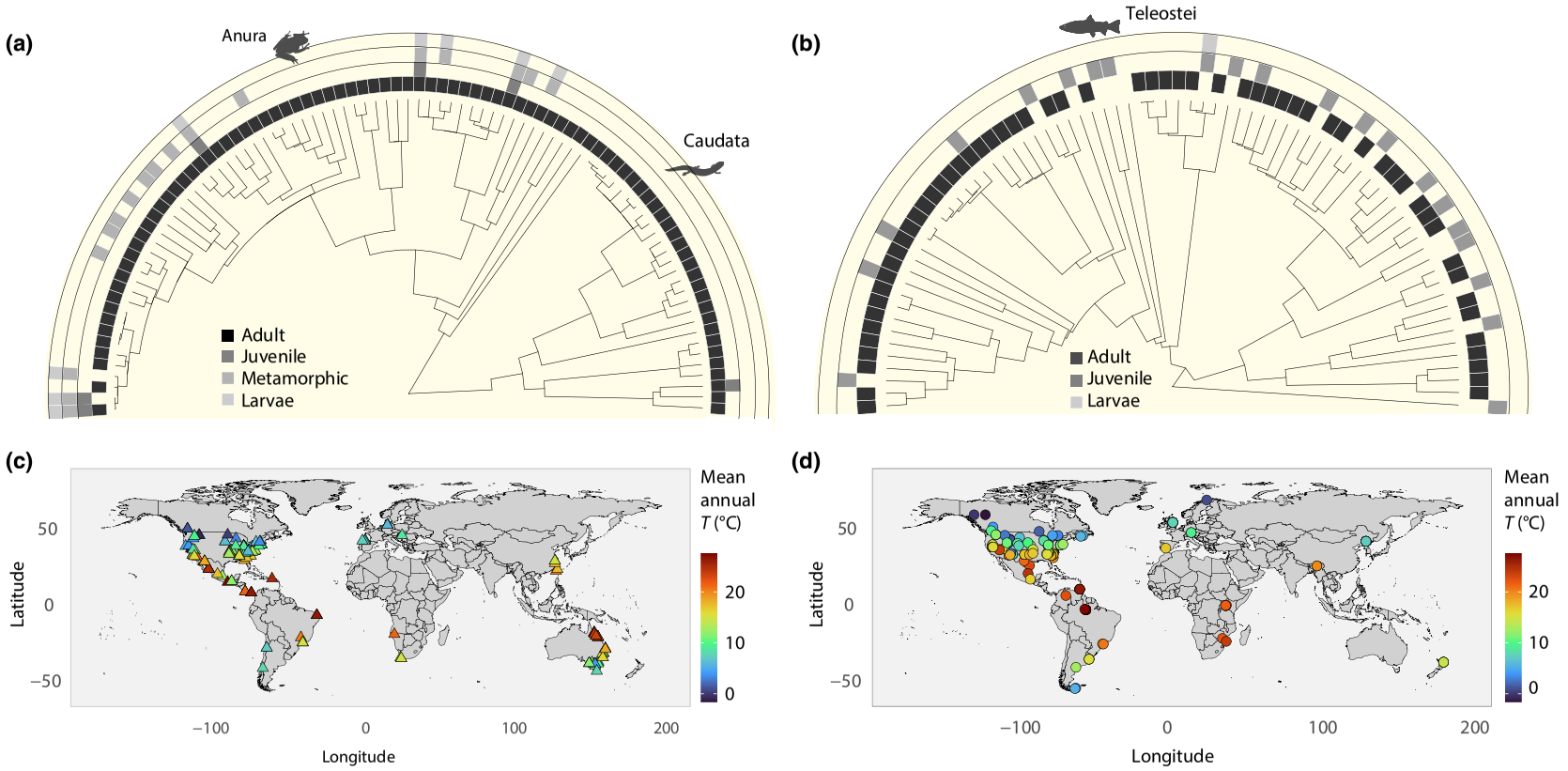

FIGURE 1 Phylogenetic, ontogenetic, and geographic background of critical thermal maximum and acclimation response ratio measurements in (a, c) amphibians (Anura and Caudata) and (b, d) freshwater fishes (Teleostei). Phylogenetic trees contain (a) 96 amphibian and (b) 93 teleost species assigned to 2 and 14 orders, respectively. Grey shaded squares indicate which life stages of a species were studied. Maps show the geographical origin and local mean temperature of (c) amphibian and (d) fish species. Phylogenetic coverage was approximately 1% within each taxon. Silhouettes were taken from PhyloPic (www.phylopic.org). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

metric (i.e., ARR). Therefore, it remains possible that this bias may also occur.

3 | RESULTS

The analysis of paired CT_{max} and ARR values included 201 experimental studies on 96 amphibian species (2 orders) (Figure 1a,c) and 144 experimental studies on 93 teleost species (14 orders) (Figure 1b,d), corresponding to a phylogenetic coverage of approximately 1% within each taxon. No data were available for Gymnophiona. Most experimental studies determined CT_{max} and ARR in adult animals. For freshwater fishes, only one study determining CT_{max} in larvae was obtained, while 20% of the data covered juveniles (Figure 1b). For amphibian species, 12% of the data was available for one or several of the early life stages, that is, larvae, metamorphs, and/or juveniles (Figure 1a).The geographic origin of amphibian and fish species displayed a bias toward temperate and subtropical regions, with 60% of all sampling sites located in North America, 10% in Australia and New Zealand, 8% in South America, 6% in Europe, and 4% in China (Figure 1c,d). The CT_{max} protocols were variable in both taxa, with acclimation times ranging from 0.5 to 150 day (mean = 11.2 day), acclimation temperatures ranging from 8.0 to 31.75°C (mean = 19.45°C), and ramping rates ranging from 0.02 to 1.0°C min^{-1} (mean = 0.75°C min^{-1}).

Across all species studied, CT_{max} ranged from 20.75 to 46.00°C (Table S1; Figure S2a). Acclimation capacity in upper thermal tolerance was positive in 97.1% of the experimental studies with an average of 0.22°C with every 1°C increase in acclimation temperature across all experimental studies and life stages, whereas the acclimation response for CT_{max} was negative (i.e., negative ARR) in 2.0% of the experimental studies. Across all species studied, ARR ranged from −0.08 to 1.68 (Table S1; Figure S2b).

For CT_{max} data of freshwater teleosts and amphibians (345 observations = number of experiments), the CIT model (73% explained variance) resulted in a classification tree with 8 internal splits and 9 terminal nodes (Figure 2). Phylogeny (order/taxon), acclimation temperature and acclimation duration were the main discriminators of CT_{max}, followed by geographic origin (annual habitat temperature, bio1) and life stage. The first split separated a group of teleost studies (mainly salmonid species) with lower CT_{max} values compared to the mean of all other studies ($p < .001$). In this group of cold-water

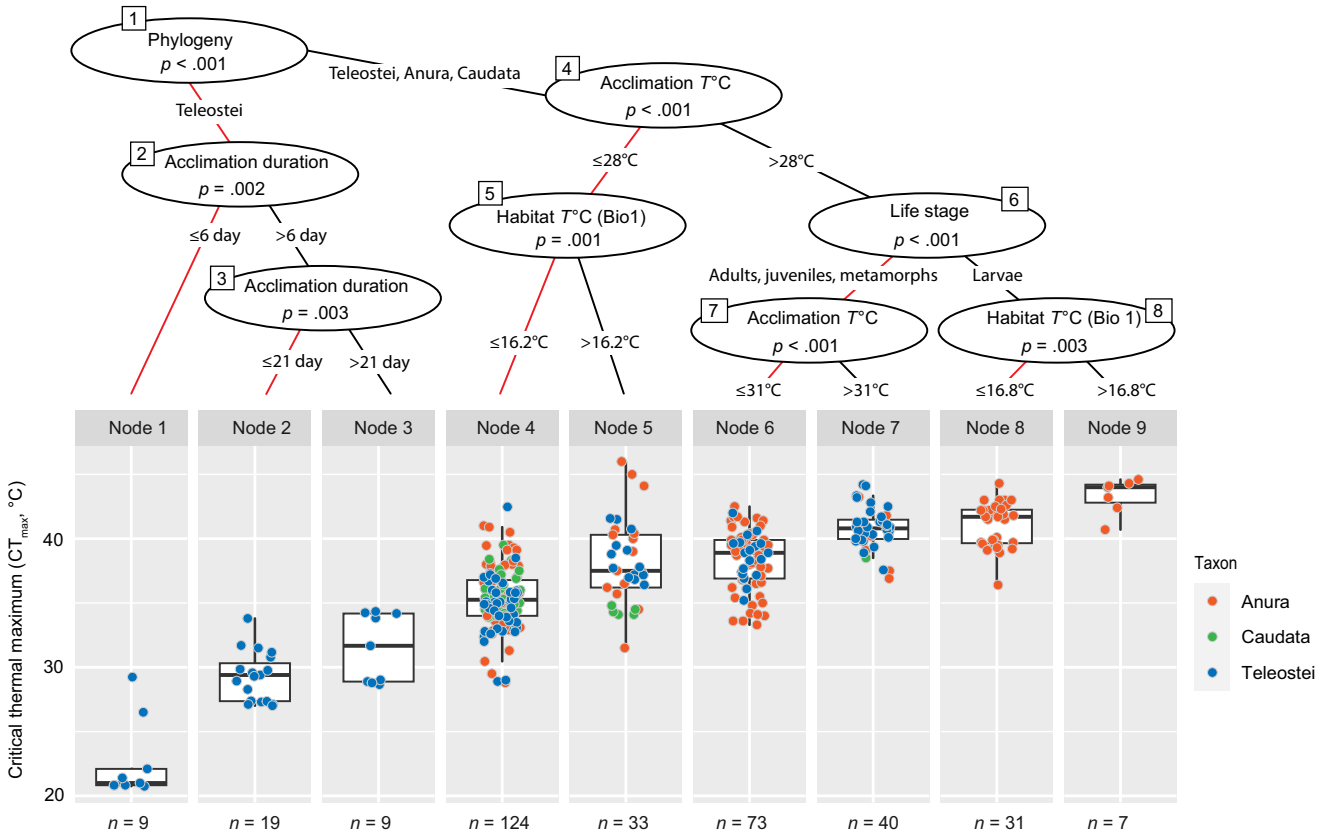

FIGURE 2 Conditional inference tree for critical thermal maximum (CT_{max}) of freshwater fish (Teleostei) and amphibians (Anura and Caudata). The sequence of internal nodes (splits) corresponds to a hierarchical structure of significant predictor variables. At each split, lines indicate the classification into groups with higher (black) and lower (red) CT_{max} values. Boxplots show the distribution of CT_{max} values (colored symbols) for each terminal node (n = number of experimental studies). Acclimation T = mean acclimation temperature used in an experiment before CT_{max} measurements (°C). Habitat T = mean annual temperature Bio1 (°C). Acclimation time = mean exposure time to acclimation temperatures before CT_{max} measurements (day).

fish, CT_{max} increased significantly with acclimation duration (nodes 1–3), with classification thresholds of split 2 and 3 defining differences between short (<6 days), intermediate (6–21 days) and long acclimation times (>21 days). For the majority of teleost and amphibian data (308 observations), CT_{max} was significantly dependent on acclimation temperature (split 4, $p < .001$), mean annual habitat temperature (Bio 1; split 5, $p = .001$) and life stage (split 6, $p < .001$). Overall, there was a positive correlation between acclimation/mean annual habitat temperature and CT_{max} (node 4–9). Split 4 separated teleosts and amphibians acclimated below or above 28°C. In the colder group (split 5), CT_{max} was higher for teleosts and amphibians that originated from warmer habitats, with a classification threshold of 16.2°C (node 4 and 5). For species acclimated above 28°C, CT_{max} differed between ontogenetic life stages (split 6), with larvae having higher tolerance limits than juveniles, metamorphs and adults. However, this classification was phylogenetically unbalanced, as all larvae were anuran species (node 8 and 9). Splits 7 and 8 show that after accounting for ontogenetic differences, CT_{max} was higher at warmer acclimation temperature (>31°C, node 6 and 7) and higher mean annual habitat temperatures (>16.8°C, node 8 and 9).

For ARR data (345 observations), the CIT model (52% explained variance) produced a classification tree with 7 internal splits and 8 terminal nodes (Figure 3). The main discriminators of ARR were phylogeny (order/taxon) and acclimation time, followed by CT_{max} methodology (ramping rate) and a minor influence of local temperature variability (isothermality, Bio 3). The first split of the classification tree separated a large number of teleost studies (102 observations, 68 species, node 1 and 2) with a higher ARR compared to the average of the other fish and amphibian studies in the dataset ($p < .001$). The relatively high thermal plasticity of the fish species in node 1 and 2 was not related to any of the variables examined. Within this group, however, ARR decreased at higher acclimation temperatures, with a classification threshold of 20°C (split 2, $p = .003$). Split 3 was based on CT_{max} methodology, classifying fish and amphibian studies into groups with an acclimation duration longer or shorter than 14 days (node 3–8). Longer acclimation generally resulted in higher ARR values (node 3–5, $p < .001$), but the acclimation effect differed according to ramping rate (split 4), phylogeny (split 5 and 6) and climate variability (split 7). When the acclimation duration exceeded 14 days, ARR studies were further classified according to ramping rate (split

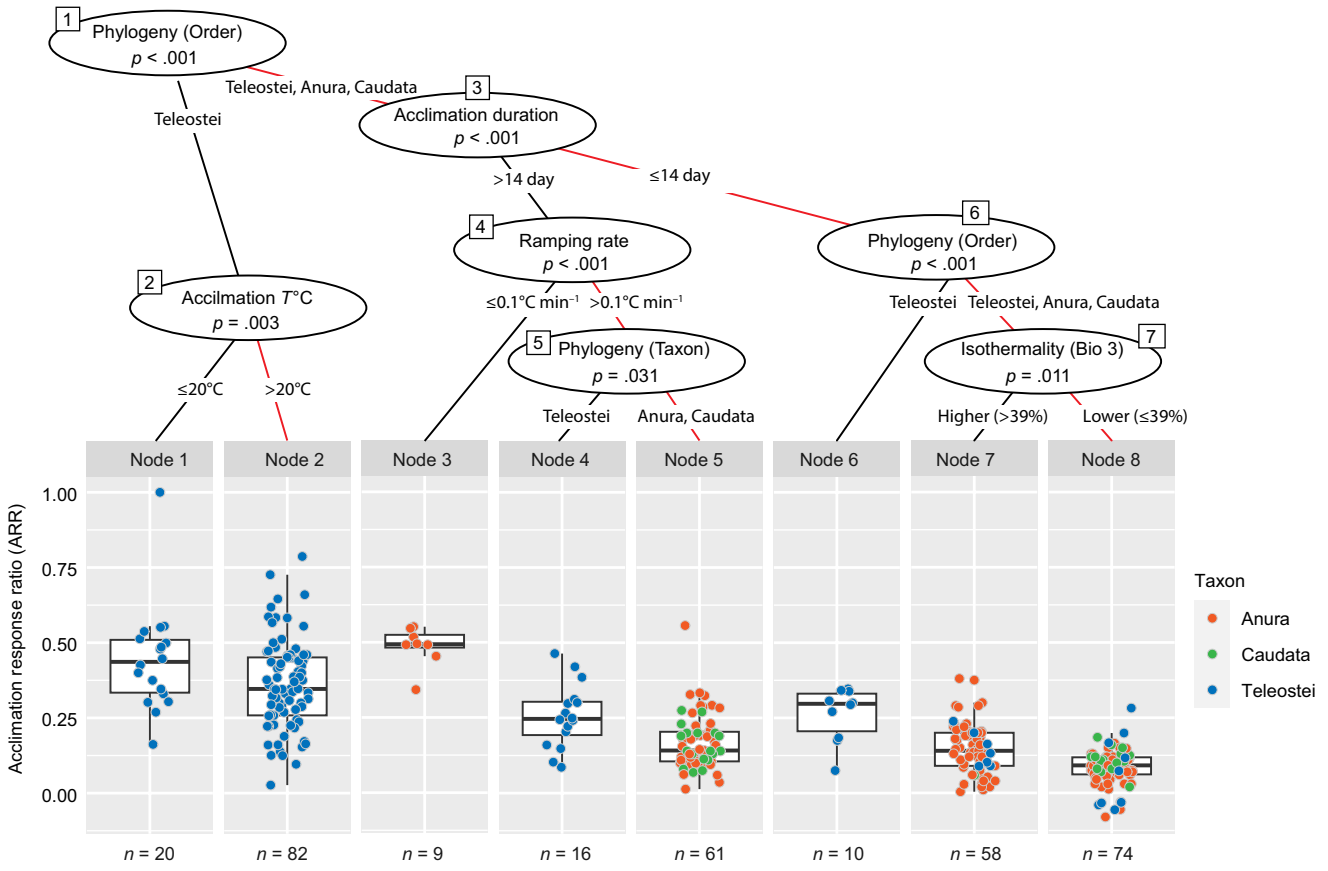

FIGURE 3 Conditional inference tree for the acclimation response ratio (ARR) of freshwater fish (Teleostei) and amphibians (Anura and Caudata). The sequence of internal nodes (splits) corresponds to a hierarchical structure of significant predictor variables. At each internal node, lines indicate the classification into groups with higher (black) and lower (red) ARR values. Boxplots show the distribution of ARR values (colored symbols) for each terminal node (n = number of experimental studies). In node 1, high outlier values ($n = 2$) were not shown for scaling reasons. Acclimation T = mean acclimation temperature used in an experiment before CT_{max} measurements (°C). Ramping rate = heating rate for CT_{max} measurements in°C per minute. Isothermality = local temperature variability Bio 3 (%). Acclimation time = mean exposure time to acclimation temperatures before CT_{max} measurements (day).

4, $p < .001$) and taxon (split 5, $p = .031$). These classifications imply higher ARR values of anurans at slow heating rates (<0.1°C min^{-1}), and higher ARR values of teleosts compared to amphibians at ramping rates >0.1°C min^{-1} (Figure 3). If the acclimation period was less than 14 days, a subsequent split occurred according to phylogenetic order (split 6, $p < .001$) and isothermality (split 7), indicating a positive relationship between ARR and local temperature variability (node 7 and 8, $p = .011$). Ontogenetic differences in ARR were not detected.

Isothermality (Bio 3; $R^2 = .708$, $p < .001$) and annual mean temperature (Bio 1; $R^2 = .696$, $p < .001$) decreased from the tropics to the polar latitudes (Figure S4). Both bioclimatic variables did not correlate with elevation (Bio 1: $R^2 = .137$, $p < .001$; Bio 3: $R^2 = .012$, $p = .046$).

4 | DISCUSSION

4.1 | Context-Dependent Drivers and Broad-Scale patterns of physiological limits

The most striking result from our analyses is that the acclimation capacity of freshwater fish was more than twice that of amphibians, indicating a strong phylogenetic signal. Our findings align with those reported in previous syntheses (Gunderson & Stillman, 2015; Morley et al., 2019; Pottier, Burke, Drobniak, et al., 2022; Rohr et al., 2018), demonstrating a higher thermal plasticity in organisms inhabiting aquatic habitats compared to their terrestrial counterparts in general, and with fish (marine and freshwater) exhibiting greater thermal plasticity compared to amphibians (Gunderson & Stillman, 2015). Compared to most (post-metamorphic) amphibians, freshwater fish are restricted to their aquatic habitat throughout their life cycle (Comte & Grenouillet, 2013). As aquatic habitats tend to have less spatial variability in operative thermal conditions than terrestrial habitats (Gunderson & Stillman, 2015; Sunday et al., 2014), behavioral thermoregulation is constrained, and freshwater fish are more likely than amphibians to use thermal plasticity to buffer against changing thermal conditions. Consequently, the capacity for thermal plasticity appears to be phylogenetically conserved between both taxa (Angilletta et al., 2002; Bodensteiner et al., 2021), depending on the ability for behavioral thermoregulation as explained by the *Bogert effect* (Bogert, 1949; Cowles & Bogert, 1944; Muñoz, 2022), rather than on the level of thermal variation to which a population is exposed to (Huey et al., 1999) as suggested by the *climate variability hypothesis* (Janzen, 1967). Moreover, unlike freshwater fishes, most amphibians undergo a habitat shift from a larval aquatic to a post-metamorphic terrestrial habitat (Shi, 2000). As an adaptive response to often shallow or temporary larval habitats (Newman, 1992), amphibian larvae display a high degree of plasticity in growth and development (Burraco et al., 2021; Kulkarni et al., 2017; Ruthsatz, Dausmann, et al., 2018, Ruthsatz, Peck, et al., 2018; Sinai et al., 2022), providing a means for increasing fitness (Schlichting & Pigliucci, 1998). Therefore, plasticity in timing of metamorphosis appears to be more important than that in thermal tolerance to reduce mortality risk (Rudolf & Rödel, 2007) due to desiccation or temperature extremes (Albecker et al., 2023; Burraco et al., 2022). This might, at least in part, explain the lack of an ontogenetic pattern in acclimation capacity in amphibians.

Unlike acclimation capacity, geographic origin was one of the primary determinants of heat tolerance in both taxa, with a higher heat tolerance in populations from regions with a higher annual mean temperature compared to populations from regions with a lower annual mean temperature. These findings support, at least in part, the *climate variability hypothesis* (Bozinovic et al., 2011; Janzen, 1967) since annual mean temperature decreases with latitude and is highest in tropical low-elevation regions. Both taxa, therefore, exhibit physiological adaptations to latitude-dependent thermal regimes to which they are exposed. Our results agree with the findings of a large body of research that has confirmed the link between physiological limits and large-scale geography based on a species' local adaptation to temperature and other associated climatic variables (e.g., Gutiérrez-Pesquera et al., 2016; Pintanel et al., 2022; Sunday et al., 2011, 2019; but not: Addo-Bediako et al., 2000; Sørensen et al., 2016). Yet, in addition to the broader literature, our synthesis indicated that CT_{max} was not only *generally* higher in populations from warmer regions as often found in low latitudes but also, importantly, varied with ontogeny. These findings emphasize the importance of assessing life stage-specific sensitivity to thermal stress as well as spatial climatic differences in conservation science. Therefore, focusing on large-scale geographical patterns for predicting how biodiversity will respond to future environmental change might bear the risk of overlooking context-dependent variation in thermal traits and thus, intraspecific differences in vulnerability to changing thermal conditions (Duarte et al., 2012; Gutiérrez-Pesquera et al., 2016). For example, Bovo et al. (2023) demonstrated that responses of tropical amphibians to climate variation were heterogenous as a consequence of intraspecific variation in physiological traits and spatial variation in climate with elevation. Furthermore, Sunday et al. (2011) and Pinsky et al. (2019) reported that the physiological sensitivity of ectotherms across all latitudes depended on the realm, with terrestrial ectotherms being less sensitive to warming than aquatic ectotherms due to their higher capacity for behavioral thermoregulation.

4.2 | Life stage-specific thermal sensitivity as a key factor in species vulnerability to climate change

In species with complex life histories such as amphibians and teleost fish, life stages differ in size, morphology, physiology, and behavior (Wilbur, 1980). Therefore, selection might promote stage-specific adaptations in thermal physiology (Enriquez-Urzelai et al., 2019; Ruthsatz, Dausmann, et al., 2022; Ruthsatz, Rakotoarison, et al., 2022). Ignoring those life stage-specific differences in thermal physiology may drastically underestimate climate vulnerability of species with consequences for successful conservation actions. Here, we found that CT_{max} but not acclimation capacity differed between life stages in amphibians, with a higher CT_{max} in larval stages.

However, this pattern was only evident when high acclimation temperatures were used in experimental set-ups and was most pronounced in larvae from habitats with a high annual mean temperature as those found in the tropics. Limnic larvae may have a reduced capacity for behavioral thermoregulation due to their limited body size impairing the movement between different microclimates (Enriquez-Urzelai et al., 2019; Kingsolver et al., 2011; Sinclair et al., 2016), making them more dependent on passive responses to temperature fluctuations. To cope with changes in temperatures, a high heat tolerance is, therefore, advantageous in early life stages (Ruthsatz, Dausmann, et al., 2022). This might be particularly true for animals that are already living close to their heat tolerance since the ontogenetic difference was only evident at high acclimation temperatures and strongest in anurans from habitats with a high annual mean temperature. In contrast, post-metamorphic stages might rather be able to select favorable microclimates by behavioral thermoregulation (Haesemeyer, 2020; Navas & Otani, 2007). This is particularly true for amphibians, as their post-metamorphic terrestrial habitats offer much spatial variability in operative thermal conditions (Gunderson & Stillman, 2015), while juvenile and adult (freshwater) fish are able to behaviorally thermoregulate by performing vertical and horizontal movements (Amat-Trigo et al., 2023; Breau et al., 2007; but not: Clark et al., 2022). Our findings are in line with the pattern found for aquatic larvae by Cupp Jr. (1980), Sherman (1980), Enriquez-Urzelai et al. (2019), and Ruthsatz, Dausmann, et al. (2022), who demonstrated a higher CT_{max} in amphibian larvae than in post-metamorphic stages. In contrast, Dahlke et al. (2020) found no difference in heat tolerance between larval and adult stages in marine and freshwater fish. Notably, our synthesis yielded only one estimate for larval CT_{max} and acclimation capacity in freshwater fish and, thus, we lack the data for any conclusion. Given that small body sizes of larvae restrict their capacity for behavioral thermoregulation, we would would expect freshwater fish to exhibit the same life stage-specific differences in thermal sensitivity observed in amphibians. In a recent study on the European common frog (*Rana temporaria*), young larvae may define the climate sensitivity of populations since that life stage exhibited the lowest acclimation capacity (Ruthsatz, Dausmann, et al., 2022). Furthermore, it is worth noting that our synthesis did neither encompass embryos nor gametes producing/spawning stages, which have recently been reported to have the lowest heat tolerance in fish (Dahlke et al., 2020, 2022; Pottier, Burke, Zhang, et al., 2022) and the lowest acclimation capacity across ectotherms (Pottier, Burke, Drobniak, et al., 2022). To better identify potential life history bottlenecks in thermal sensitivity in amphibian, fish and other taxa inhabiting freshwater, future studies should adopt a more comprehensive approach by considering a wider range of life stages within species.

4.3 | Understanding context-dependent physiological adaptation in ectotherms

Global syntheses on physiological studies can help us determine the winners and losers of climate change through assessment of broad-scale patterns of species' thermal limits and acclimation capacity for modifying their thermal tolerance (Somero, 2010). This knowledge, in turn, enables us to develop suitable conservation strategies to mitigate the negative effects of climate change. However, our key findings emphasize that assessing species' vulnerability to changing thermal conditions based on large-scale geographic and/or phylogenetic patterns in thermal traits might cover up context-dependent physiological adaptations. In other words, tropical ectothermic species are considered particularly vulnerable to global warming as they live close to their physiological limits and have poor acclimation ability (Huey et al., 2009; Sunday et al., 2014; Tewksbury et al., 2008), but such generalizations might for instance ignore intraspecific variation in physiological limits across variation in climate with elevation (Bovo et al., 2023). Physiological adaptations are driven by the interplay between microclimate temperature heterogeneity and the behavioral thermoregulatory abilities of ectotherms (Huey et al., 2012; Pincebourde et al., 2016; present study) depending on their habitat characteristics (Kulkarni et al., 2017; Pinsky et al., 2019), ontogeny (Enriquez-Urzelai et al., 2019; Ruthsatz, Dausmann, et al., 2022), life history traits such as body size (Peralta-Maraver & Rezende, 2021; Rubalcaba & Olalla-Tárraga, 2020) or activity patterns (Navas & Otani, 2007; Ruthsatz, Rakotoarison, et al., 2022), and/or energy balance (Muñoz, 2022; Pörtner et al., 2005). Physiological traits and limits are consequently rather evolutionary driven dynamic concepts than fixed values for a species (Bovo et al., 2018, 2023; Navas et al., 2022). In order to improve predictions of climate change impacts on biodiversity, it is imperative to deepen our understanding of context-dependent physiological adaptations (Meek et al., 2023), thereby advancing the development of suitable conservation measures/strategies that incorporate evolutionarily enlightened perspectives (Ashley et al., 2003; Cook & Sgrò, 2018) beyond the species level (Figure 4).

5 | CONCLUSION

There is a growing body of physiological studies assessing thermal limits and acclimation capacity of species, investigating physiological systems setting these limits to better predict shifts in the productivity and species distribution patterns in a warming world. Our synthesis points to representation biases in taxonomy, species' biogeographic distribution, life stage, and biases resulting from non-standardized study design. Here, we found the influence of life stage, phylogeny, and thermal adaptation to depend on acclimation duration and acclimation temperature of the animals and the ramping rate used, underscoring the importance of a thoughtful selection of the methodological approach. Notably, due to the biases present in existing data sets, most results from subsequent analyses (including

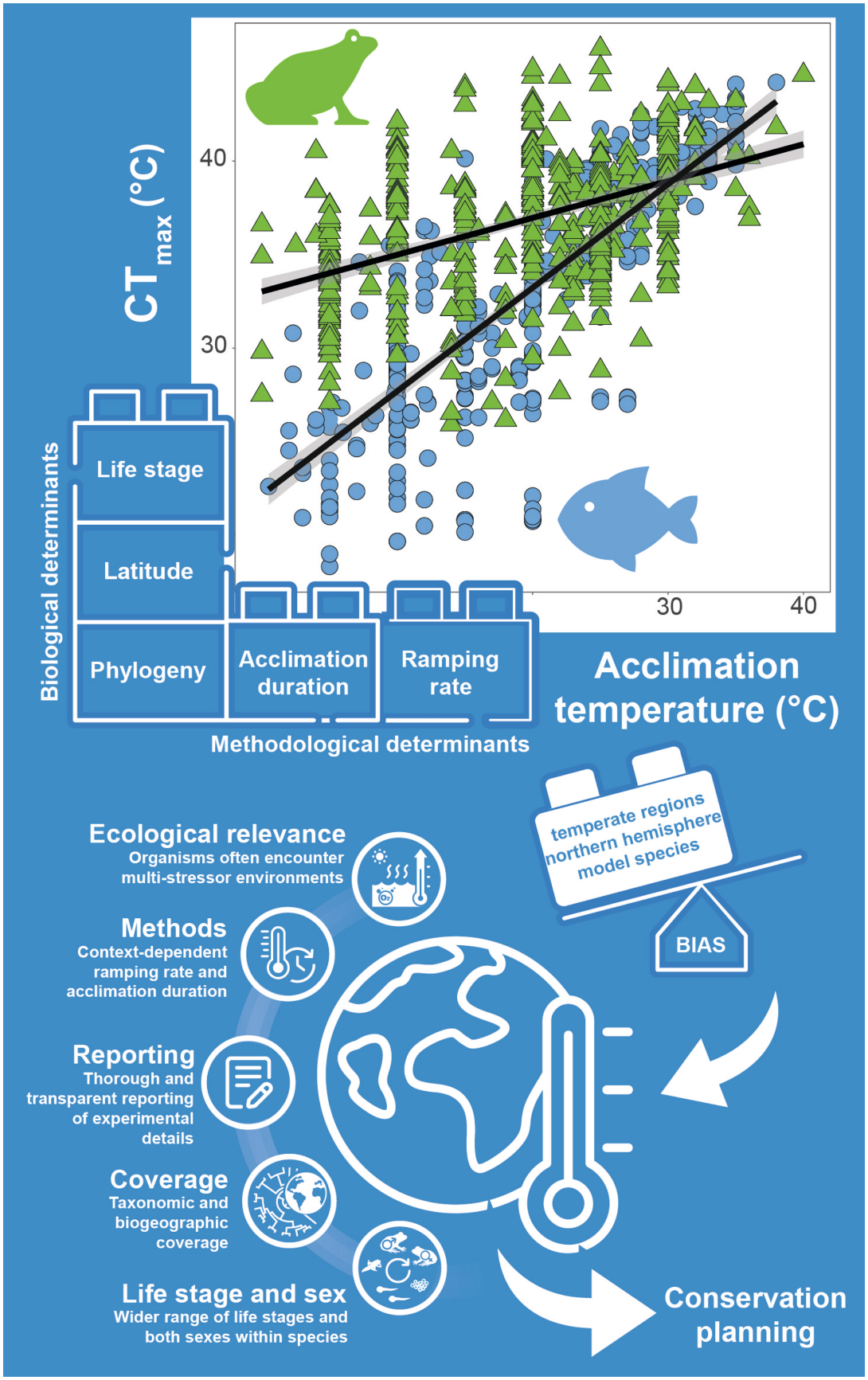

FIGURE 4 Synthesis of biological and methodological determinants as well as key directions for future research on acclimation capacity in amphibians and freshwater fish to advance the application of thermal traits in assessing species' and populations' vulnerability to climate change. See text for further details.

those presented here) cannot be generalized to all geographic regions, life stages, and (taxonomic) groups, which limits the ability to predict organismal responses to global change (White et al., 2021). Therefore, we conclude our synthesis by addressing those data inadequacies and proposing methods to enhance data collection presented in five themes (Figure 4):

5.1 | Biogeographic and taxonomic coverage

We found geographical trends in physiological limits associated with bioclimatic conditions at different latitudes. Thus, additional research is needed in poorly represented (mostly tropical) regions that generally correspond to low- and middle-income countries (King, 2004). Addressing this issue can yield additional, important insights, as such geographic bias in existing data sets has been shown to limit our ability to predict organismal responses in these less-studied regions (White et al., 2021). Our synthesis highlights that most experiments have been conducted in North America, Europe, and Australia and information gaps exist for most parts of Neotropics, Africa and Sino-Oriental regions. Those regions harbor the highest diversity of species for both anurans and freshwater fishes (Jenkins et al., 2013; van der Sleen & Albert, 2022). Such regional differences in research effort are common in conservation science (McLaughlin et al., 2022; Schiesari et al., 2007; Sinai et al., 2022; Winter et al., 2016; White et al., 2021) despite the fact that under-studied regions contain the vast majority of global biodiversity hotspots (Mittermeier et al., 2011). Furthermore, most of these experiments used species that are common, widely distributed, and/or easily obtained by researchers. Studies on other species (particularly those already in decline) are needed to avoid taxonomic bias and reach stronger conclusions on whether specific taxa might be more sensitive to global warming (da Silva et al., 2020). Additionally, there may be an elevation bias in sampling, as most available data represent lowland rather than mountain species. As, for example, CT_{max} of tropical and subtropical amphibian species has been shown to vary within the same latitude (Duarte et al., 2012; Gutiérrez-Pesquera et al., 2016), we urge future studies to focus on elevation gradients as well as cross-latitudinal sampling, especially in tropical high-mountain populations (Bovo et al., 2023).

5.2 | Relevance of life stage and sex

We urge future studies to measure a wider range of life stages and to measure both sexes within species to better identify thermal bottlenecks and assess climate change risks (Dahlke et al., 2020; Klockmann et al., 2017). All of the summaries to date likely overestimate physiological limits since most studies have been performed on adults, and thermal tolerance increases (Klockmann et al., 2017; Rubalcaba & Olalla-Tárraga, 2020; but not: Di Santo & Lobel, 2017) and acclimation capacity decreases (Pottier et al., 2021) with body size. Furthermore, after sexual maturity, females and males differ in a wide range of morphological, physiological, and behavioral aspects as well as in their energetic investment in gamete production (Hayward & Gillooly, 2011). A recent meta-analysis across ectothermic taxa revealed that the acclimation capacity differed between adult males and females in wild-caught animals (Pottier et al., 2021). Furthermore, Dahlke et al. (2020) found narrower thermal tolerance ranges in spawning females and van Heerwaarden and Sgrò (2021) demonstrated that a low heat tolerance of male fertility is a critical bottleneck in insects.

5.3 | Ecological relevance

Future laboratory experiments should adopt a more comprehensive and multifaceted approach for higher ecological relevance of thermal trait estimates (Desforges et al., 2023). Under natural conditions, organisms must often cope with multiple simultaneously occurring environmental stressors (Gunderson et al., 2016; Rohr & Palmer, 2013) such as declining dissolved oxygen levels in freshwater habitats due to climate-induced temperature increases (Pörtner & Peck, 2010). As thermal limits are shaped by oxygen availability (Pörtner, 2001, 2010), organisms might exhibit lower thermal limits under natural conditions. Moreover, exposure to pollutants might reduce thermal tolerance (Little & Seebacher, 2015) or acclimation capacity (Ruthsatz, Peck, et al., 2018) due to increased metabolic demands of detoxification processes or disruption of endocrine pathways involved in physiological acclimation. Physiological responses to increased water temperature as performed in the experimental studies summarized here (i.e., a single stressor) may not align with observed responses of individuals in the natural environments with multiple stressors (Katzenberger et al., 2014; Potts et al., 2021).

5.4 | Methodological approach

Customizing protocols to account for organismal and context-dependent variations in physiological limits (e.g., body size, life stage, sex, thermal history) will allow researchers to obtain more ecologically relevant estimates to inform conservation efforts. The application of an acute thermal ramping rate and a standardized endpoint such as the LOE are used to measure critical thermal limits (Becker & Genoway, 1979). The estimates are sensitive to differences in the methods. For example, faster ramping (heating) rates tend to yield higher thermal tolerance estimates compared to slower ramping rates (Kovacevic et al., 2019; Moyano et al., 2017; Penman et al., 2023). Furthermore, measuring several endpoints (LOE/LRR, onset of spasms/heat rigor) if possible (Cowan et al., 2023; Wu & Kam, 2005) might facilitate comparisons between different taxonomic groups and/or experiments (Lutterschmidt & Hutchison, 1997b). Using wild-collected animals is important as those reared in the laboratory may have physiology traits that differ from wild conspecifics (Morgan et al., 2022; Pottier et al., 2021). Methodological recommendations have been recently published and comparable methods are needed

to compare thermal limits of different life stages (Cowan et al., 2023; Desforges et al., 2023).

5.5 | Through reporting of research details

Thorough and transparent reporting of experimental details in empirical studies such as sampling location and animal origin, among others, is required to enhance the comparability of studies on thermal traits. Furthermore, most studies working on adults did not report the sex of animals despite the potential for sex (or reproductive state) to be important factors in thermal sensitivity. Additionally, reporting microhabitat temperatures (i.e., in-site temperatures) will improve our understanding of thermal adaptation at the population-level. The ability to make broad-scale comparisons of thermal tolerance across taxa, life stages, and regions will be enhanced when studies report as much methodological detail as possible. Consequently, these future studies will contribute more robust estimates of climate vulnerability needed to guide climate change interventions.

By considering our recommendations, future studies will be more comparable, facilitating the utilization of respective findings in large-scale studies and models that assess species vulnerability and thus, population dynamics under global warming.

AUTHOR CONTRIBUTIONS

Katharina Ruthsatz: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; supervision; validation; visualization; writing – original draft. **Flemming Dahlke:** Formal analysis; investigation; validation; visualization; writing – original draft. **Katharina Alter:** Methodology; validation; writing – review and editing. **Sylke Wohlrab:** Formal analysis; methodology; validation; visualization; writing – review and editing. **Paula C. Eterovick:** Methodology; validation; writing – review and editing. **Mariana L. Lyra:** Methodology; validation; writing – review and editing. **Sven Gippner:** Methodology; writing – review and editing. **Steven J. Cooke:** Validation; writing – review and editing. **Myron A. Peck:** Conceptualization; methodology; supervision; writing – original draft.

ACKNOWLEDGEMENTS

We would like to thank the German Research Foundation (DFG) for providing financial support to KR and PCE for this study and the Universität Hamburg for providing financial support to KR by the PostDoc1st award. We thank M. Multsch for assisting with the data visualization and U. Enriquez-Urzelai and M. H. Bernal for providing data on request. We thank Trina Rytwinski for her guidance on the statistical approach. We are grateful for the valuable comments provided by two anonymous reviewers. We are particularly grateful to all authors of the articles included in our systematic literature review, whose effort and work made the present study possible. Open Access funding enabled and organized by Projekt DEAL.

FUNDING INFORMATION

KR was supported by a PhD award (PostDoc1st) from the University of Hamburg. The German Research Foundation (DFG) project (459850971; A new perspective on amphibians and global change: Detecting sublethal effects of environmental stress as agents of silent population declines) supported KR and PCE. MLL was supported by the São Paulo Research Foundation in Brazil (FAPESP #2021/10639-5).

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in in the figshare data repository under https://figshare.com/s/57775032a0b79c416ef2 (https://doi.org/10.6084/m9.figshare.24872133).

ORCID

Katharina Ruthsatz https://orcid.org/0000-0002-3273-2826
Flemming Dahlke https://orcid.org/0000-0003-0095-2362
Katharina Alter https://orcid.org/0000-0002-1801-748X
Sylke Wohlrab https://orcid.org/0000-0003-3190-0880
Paula C. Eterovick https://orcid.org/0000-0002-1316-1255
Mariana L. Lyra https://orcid.org/0000-0001-6519-9469
Sven Gippner https://orcid.org/0000-0003-2621-1001
Steven J. Cooke https://orcid.org/0000-0002-5407-0659
Myron A. Peck https://orcid.org/0000-0001-7423-1854

REFERENCES

Addo-Bediako, A., Chown, S. L., & Gaston, K. J. (2000). Thermal tolerance, climatic variability and latitude. *Proceedings of the Royal Society of London, Series B: Biological Sciences*, *267*(1445), 739–745.

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, *19*(6), 716–723. https://doi.org/10.1109/TAC.1974.1100705

Albecker, M. A., Strobel, S. M., & Womack, M. C. (2023). Developmental plasticity in anurans: Meta-analysis reveals effects of larval environments on size at metamorphosis and timing of metamorphosis. *Integrative and Comparative Biology*, *63*, 714–729. https://doi.org/10.1093/icb/icad059

Albert, J. S., Carvalho, T. P., Petry, P., Holder, M. A., Maxime, E. L., Espino, J., Corahua, I., Quispe, R., Rengifo, B., Ortega, H., & Reis, R. E. (2011). Aquatic biodiversity in the Amazon: Habitat specialization and geographic isolation promote species richness. *Animals*, *1*(2), 205–241. https://doi.org/10.3390/ani1020205

Amat-Trigo, F., Andreou, D., Gillingham, P. K., & Britton, J. R. (2023). Behavioural thermoregulation in cold-water freshwater fish: Innate resilience to climate warming? *Fish and Fisheries*, *24*(1), 187–195. https://doi.org/10.1111/faf.12720

Angilletta, M. J., Jr., Niewiarowski, P. H., & Navas, C. A. (2002). The evolution of thermal physiology in ectotherms. *Journal of Thermal Biology*, *27*(4), 249–268. https://doi.org/10.1016/S0306-4565(01)00094-8

Ashley, M. V., Willson, M. F., Pergams, O. R., O'Dowd, D. J., Gende, S. M., & Brown, J. S. (2003). Evolutionarily enlightened management.

Biological Conservation, *111*(2), 115–123. https://doi.org/10.1016/S0006-3207(02)00279-3

Becker, C. D., & Genoway, R. G. (1979). Evaluation of the critical thermal maximum for determining thermal tolerance of freshwater fish. *Environmental Biology of Fishes*, *4*, 245–256. https://doi.org/10.1007/BF00005481

Bennett, J. M., Calosi, P., Clusella-Trullas, S., Martínez, B., Sunday, J., Algar, A. C., Araújo, M. B., Hawkins, B. A., Keith, S., Kühn, I., Rahbek, C., Rodríguez, L., Singer, A., Villalobos, F., Ángel Olalla-Tárraga, M., & Morales-Castilla, I. (2018). GlobTherm, a global database on thermal tolerances for aquatic and terrestrial organisms. *Scientific Data*, *5*, 180022.

Bodensteiner, B. L., Agudelo-Cantero, G. A., Arietta, A. A., Gunderson, A. R., Muñoz, M. M., Refsnider, J. M., & Gangloff, E. J. (2021). Thermal adaptation revisited: How conserved are thermal traits of reptiles and amphibians? *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, *335*(1), 173–194. https://doi.org/10.1002/jez.2414

Bogert, C. M. (1949). Thermoregulation in reptiles, a factor in evolution. *Evolution*, *3*(3), 195–211.

Bovo, R. P., Navas, C. A., Tejedo, M., Valença, S. E., & Gouveia, S. F. (2018). Ecophysiology of amphibians: Information for best mechanistic models. *Diversity*, *10*(4), 118. https://doi.org/10.3390/d10040118

Bovo, R. P., Simon, M. N., Provete, D. B., Lyra, M., Navas, C. A., & Andrade, D. V. (2023). Beyond Janzen's hypothesis: How amphibians that climb tropical mountains respond to climate variation. *Integrative Organismal Biology*, *5*(1), obad009. https://doi.org/10.1093/iob/obad009

Bozinovic, F., Calosi, P., & Spicer, J. I. (2011). Physiological correlates of geographic range in animals. *Annual Review of Ecology, Evolution, and Systematics*, *42*, 155–179. https://doi.org/10.1146/annurev-ecolsys-102710-145055

Breau, C., Cunjak, R. A., & Bremset, G. (2007). Age-specific aggregation of wild juvenile Atlantic salmon *Salmo salar* at cool water sources during high temperature events. *Journal of Fish Biology*, *71*(4), 1179–1191. https://doi.org/10.1111/j.1095-8649.2007.01591.x

Burraco, P., Laurila, A., & Orizaola, G. (2021). Limits to compensatory responses to altered phenology in amphibian larvae. *Oikos*, *130*(2), 231–239. https://doi.org/10.1111/oik.07919

Burraco, P., Rendón, M. A., Díaz-Paniagua, C., & Gomez-Mestre, I. (2022). Maintenance of phenotypic plasticity is linked to oxidative stress in spadefoot toad larvae. *Oikos*, *2022*(5), e09078. https://doi.org/10.1111/oik.09078

Calosi, P., Bilton, D. T., & Spicer, J. I. (2008). Thermal tolerance, acclimatory capacity and vulnerability to global climate change. *Biology Letters*, *4*(1), 99–102. https://doi.org/10.1098/rsbl.2007.0408

Campos, D. F., Amanajás, R. D., Almeida-Val, V. M., & Val, A. L. (2021). Climate vulnerability of south American freshwater fish: Thermal tolerance and acclimation. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, *335*(9–10), 723–734. https://doi.org/10.1002/jez.2452

Capon, S. J., Stewart-Koster, B., & Bunn, S. E. (2021). Future of freshwater ecosystems in a 1.5°C warmer world. *Frontiers in Environmental Science*, *9*, 596. https://doi.org/10.3389/fenvs.2021.784642

Carilo Filho, L. M., Gomes, L., Katzenberger, M., Sole, M., & Orrico, V. G. (2022). There and back again: A meta-analytical approach on the influence of acclimation and altitude in the upper thermal tolerance of amphibians and reptiles. *Frontiers in Ecology and Evolution*, *10*, 1017255. https://doi.org/10.3389/fevo.2022.1017255

Chang, J., Rabosky, D. L., Smith, S. A., & Alfaro, M. E. (2019). An R package and online resource for macroevolutionary studies using the ray-finned fish tree of life. *Methods in Ecology and Evolution*, *10*(7), 1118–1124. https://doi.org/10.1111/2041-210X.13182

Chown, S. L., Jumbam, K. R., Sørensen, J. G., & Terblanche, J. S. (2009). Phenotypic variance, plasticity and heritability estimates of critical thermal limits depend on methodological context. *Functional Ecology*, *23*(1), 133–140. https://doi.org/10.1111/j.1365-2435.2008.01481.x

Cicchino, A. S., Shah, A. A., Forester, B. R., Dunham, J. B., Poff, N. L., Ghalambor, C. K., & Funk, W. C. (2023). Acclimation capacity of critical thermal maximum varies among populations: Consequences for estimates of vulnerability. *Ecosphere*, *14*(11), e4691. https://doi.org/10.1002/ecs2.4691

Clark, T. D., Scheuffele, H., Pratchett, M. S., & Skeeles, M. R. (2022). Behavioural temperature regulation is a low priority in a coral reef fish (*Plectropomus leopardus*): Insights from a novel behavioural thermoregulation system. *Journal of Experimental Biology*, *225*(18), jeb244212. https://doi.org/10.1242/jeb.244212

Claussen, D. L. (1977). Thermal acclimation in ambystomatid salamanders. *Comparative Biochemistry and Physiology—Part A: Physiology*, *58*(4), 333–340. https://doi.org/10.1016/0300-9629(77)90150-5

Closs, G. P., Angermeier, P. L., Darwall, W. R., & Balcombe, S. R. (2016). Why are freshwater fish so threatened. In G. P. Closs, M. Krkosek, & J. D. Olden (Eds.), *Conservation of freshwater fishes* (pp. 37–74). Cambridge University Press.

Comte, L., & Grenouillet, G. (2013). Do stream fish track climate change? Assessing distribution shifts in recent decades. *Ecography*, *36*(11), 1236–1246. https://doi.org/10.1111/j.1600-0587.2013.00282.x

Comte, L., & Olden, J. D. (2017a). Climatic vulnerability of the world's freshwater and marine fishes. *Nature Climate Change*, *7*(10), 718–722. https://doi.org/10.1038/nclimate3382

Comte, L., & Olden, J. D. (2017b). Evolutionary and environmental determinants of freshwater fish thermal tolerance and plasticity. *Global Change Biology*, *23*(2), 728–736. https://doi.org/10.1111/gcb.13427

Cook, C. N., & Sgrò, C. M. (2018). Understanding managers' and scientists' perspectives on opportunities to achieve more evolutionarily enlightened management in conservation. *Evolutionary Applications*, *11*(8), 1371–1388. https://doi.org/10.1111/eva.12631

Cowan, Z. L., Andreassen, A. H., De Bonville, J., Green, L., Binning, S. A., Silva-Garay, L., Jutfelt, F., & Sundin, J. (2023). A novel method for measuring acute thermal tolerance in fish embryos. *Conservation. Physiology*, *11*(1), coad061. https://doi.org/10.1093/conphys/coad061

Cowles, R. B., & Bogert, C. M. (1944). A preliminary study of the thermal requirements of desert reptiles. *Bulletin of the AMNH*, *83*(5), 265–296. http://hdl.handle.net/2246/1237

Cupp Jr., P. V. (1980). Thermal tolerance of five salientian amphibians during development and metamorphosis. *Herpetologica*, *36*(3), 234–244. https://www.jstor.org/stable/3891820

da Silva, A. F., Malhado, A. C., Correia, R. A., Ladle, R. J., Vital, M. V., & Mott, T. (2020). Taxonomic bias in amphibian research: Are researchers responding to conservation need? *Journal for Nature Conservation*, *56*, 125829. https://doi.org/10.1016/j.jnc.2020.125829

Dahlke, F., Butzin, M., Wohlrab, S., & Pörtner, H. O. (2022). Reply to: Methodological inconsistencies define thermal bottlenecks in fish life cycle. *Evolutionary Ecology*, *36*(2), 293–298.

Dahlke, F. T., Wohlrab, S., Butzin, M., & Pörtner, H. O. (2020). Thermal bottlenecks in the life cycle define climate vulnerability of fish. *Science*, *369*(6499), 65–70. https://doi.org/10.1126/science.aaz3658

Desforges, J. E., Birnie-Gauvin, K., Jutfelt, F., Gilmour, K. M., Eliason, E. J., Dressler, T. L., McKenzie, D. J., Bates, A. E., Lawrence, M. J., Fangue, N., & Cooke, S. J. (2023). The ecological relevance of critical thermal maxima methodology for fishes. *Journal of Fish Biology*, *102*(5), 1000–1016. https://doi.org/10.1111/jfb.15368

Deutsch, C. A., Tewksbury, J. J., Huey, R. B., Sheldon, K. S., Ghalambor, C. K., Haak, D. C., & Martin, P. R. (2008). Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(18), 6668–6672. https://doi.org/10.1073/pnas.0709472105

Di Santo, V., & Lobel, P. S. (2017). Body size and thermal tolerance in tropical gobies. *Journal of Experimental Marine Biology and Ecology*, *487*, 11–17. https://doi.org/10.1016/j.jembe.2016.11.007

Duarte, H., Tejedo, M., Katzenberger, M., Marangoni, F., Baldo, D., Beltrán, J. F., Martí, D. A., Richter-Boix, A., & Gonzalez-Voyer, A. (2012). Can amphibians take the heat? Vulnerability to climate warming in subtropical and temperate larval amphibian communities. *Global Change Biology*, *18*(2), 412–421. https://doi.org/10.1111/j.1365-2486.2011.02518.x

Enriquez-Urzelai, U., Sacco, M., Palacio, A. S., Pintanel, P., Tejedo, M., & Nicieza, A. G. (2019). Ontogenetic reduction in thermal tolerance is not alleviated by earlier developmental acclimation in *Rana temporaria*. *Oecologia*, *189*, 385–394. https://doi.org/10.1007/s00442-019-04342-y

Enriquez-Urzelai, U., Tingley, R., Kearney, M. R., Sacco, M., Palacio, A. S., Tejedo, M., & Nicieza, A. G. (2020). The roles of acclimation and behaviour in buffering climate change impacts along elevational gradients. *Journal of Animal Ecology*, *89*(7), 1722–1734. https://doi.org/10.1111/1365-2656.13222

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*(12), 4302–4315. https://doi.org/10.1002/joc.5086

Franks, S. J., & Hoffmann, A. A. (2012). Genetics of climate change adaptation. *Annual Review of Genetics*, *46*, 185–208. https://doi.org/10.1146/annurev-genet-110711-155511

Fry, F. (1947). Effects of the environment on animal activity. *Publications of the Ontario Fisheries Research Laboratory*, *55*(68), 1–62.

Ghalambor, C. K., Huey, R. B., Martin, P. R., Tewksbury, J. J., & Wang, G. (2006). Are mountain passes higher in the tropics? Janzen's hypothesis revisited. *Integrative and Comparative Biology*, *46*(1), 5–17. https://doi.org/10.1093/icb/icj003

Gunderson, A. R., Armstrong, E. J., & Stillman, J. H. (2016). Multiple stressors in a changing world: The need for an improved perspective on physiological responses to the dynamic marine environment. *Annual Review of Marine Science*, *8*, 357–378. https://doi.org/10.1146/annurev-marine-122414-033953

Gunderson, A. R., & Leal, M. (2016). A conceptual framework for understanding thermal constraints on ectotherm activity with implications for predicting responses to global change. *Ecology Letters*, *19*(2), 111–120. https://doi.org/10.1111/ele.12552

Gunderson, A. R., & Stillman, J. H. (2015). Plasticity in thermal tolerance has limited potential to buffer ectotherms from global warming. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1808), 20150401. https://doi.org/10.1098/rspb.2015.0401

Gutiérrez-Pesquera, L. M., Tejedo, M., Camacho, A., Enriquez-Urzelai, U., Katzenberger, M., Choda, M., Pintanel, P., & Nicieza, A. G. (2022). Phenology and plasticity can prevent adaptive clines in thermal tolerance across temperate mountains: The importance of the elevation-time axis. *Ecology and Evolution*, *12*(10), e9349. https://doi.org/10.1002/ece3.9349

Gutiérrez-Pesquera, L. M., Tejedo, M., Olalla-Tárraga, M. Á., Duarte, H., Nicieza, A., & Solé, M. (2016). Testing the climate variability hypothesis in thermal tolerance limits of tropical and temperate tadpoles. *Journal of Biogeography*, *43*(6), 1166–1178. https://doi.org/10.1111/jbi.12700

Haesemeyer, M. (2020). Thermoregulation in fish. *Molecular and Cellular Endocrinology*, *518*, 110986. https://doi.org/10.1016/j.mce.2020.110986

Hayward, A., & Gillooly, J. F. (2011). The cost of sex: Quantifying energetic investment in gamete production by males and females. *PLoS One*, *6*(1), e16557. https://doi.org/10.1371/journal.pone.0016557

Hijmans, R. J., Ghosh, A., & Mandel, A. (2022). geodata: Download geographic data. R package version 0.4-11. https://CRAN.R-project.org/package=geodata

Hocking, D. J., & Babbitt, K. J. (2014). Amphibian contributions to ecosystem services. *Herpetological Conservation and Biology*, *9*(1), 1–17.

Hoffmann, A. A., & Sgró, C. M. (2011). Climate change and evolutionary adaptation. *Nature*, *470*, 479–485. https://doi.org/10.1038/nature09670

Hothorn, T., & Zeileis, A. (2015). Partykit: A modular toolkit for recursive partytioning in R. *The Journal of Machine Learning Research*, *16*(1), 3905–3909.

Huey, R. B., Berrigan, D., Gilchrist, G. W., & Herron, J. C. (1999). Testing the adaptive significance of acclimation: A strong inference approach. *American Zoologist*, *39*(2), 323–336. https://doi.org/10.1093/icb/39.2.323

Huey, R. B., Deutsch, C. A., Tewksbury, J. J., Vitt, L. J., Hertz, P. E., Álvarez Pérez, H. J., & Garland, T., Jr. (2009). Why tropical forest lizards are vulnerable to climate warming. *Proceedings of the Royal Society B: Biological Sciences*, *276*(1664), 1939–1948. https://doi.org/10.1098/rspb.2008.1957

Huey, R. B., Kearney, M. R., Krockenberger, A., Holtum, J. A., Jess, M., & Williams, S. E. (2012). Predicting organismal vulnerability to climate warming: Roles of behaviour, physiology and adaptation. *Philosophical Transactions of the Royal Society, B: Biological Sciences*, *367*(1596), 1665–1679. https://doi.org/10.1098/rstb.2012.0005

Hutchison, V. H. (1961). Critical thermal maxima in salamanders. *Physiological Zoology*, *34*(2), 92–125. https://doi.org/10.1086/physzool.34.2.30152688

Illing, B., Downie, A. T., Beghin, M., & Rummer, J. L. (2020). Critical thermal maxima of early life stages of three tropical fishes: Effects of rearing temperature and experimental heating rate. *Journal of Thermal Biology*, *90*, 102582. https://doi.org/10.1016/j.jtherbio.2020.102582

IPCC. (2021). Summary for policymakers. In *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. https://doi.org/10.1017/9781009157896.001

ISI WOS. (2021). *Thomson scientific*. Web of Science. http://scientific.thomsonreuters.com/products/wos/

Janzen, D. H. (1967). Why mountain passes are higher in the tropics. *The American Naturalist*, *101*(919), 233–249. https://doi.org/10.1086/282487

Jenkins, C. N., Pimm, S. L., & Joppa, L. N. (2013). Global patterns of terrestrial vertebrate diversity and conservation. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(28), E2602–E2610. https://doi.org/10.1073/pnas.1302251110

Katzenberger, M., Hammond, J., Duarte, H., Tejedo, M., Calabuig, C., & Relyea, R. A. (2014). Swimming with predators and pesticides: How environmental stressors affect the thermal physiology of tadpoles. *PLoS One*, *9*(5), e98265. https://doi.org/10.1371/journal.pone.0098265

King, D. A. (2004). The scientific impact of nations. *Nature*, *430*(6997), 311–316.

Kingsolver, J. G., Arthur Woods, H., Buckley, L. B., Potter, K. A., MacLean, H. J., & Higgins, J. K. (2011). Complex life cycles and the responses of insects to climate change. *Integrative and Comparative Biology*, *51*(5), 719–732. https://doi.org/10.1093/icb/icr015

Kingsolver, J. G., & Huey, R. B. (1998). Evolution ary analyses of morphological and physiological plasticity in thermally variable environments. *American Zoologist*, *38*(3), 545–560. https://doi.org/10.1093/icb/38.3.545

Klockmann, M., Günter, F., & Fischer, K. (2017). Heat resistance throughout ontogeny: Body size constrains thermal tolerance. *Global Change Biology*, *23*(2), 686–696. https://doi.org/10.1111/gcb.13407

Kovacevic, A., Latombe, G., & Chown, S. L. (2019). Rate dynamics of ectotherm responses to thermal stress. *Proceedings of the Royal Society B*, *286*(1902), 20190174. https://doi.org/10.1098/rspb.2019.0174

Kulkarni, S. S., Denver, R. J., Gomez-Mestre, I., & Buchholz, D. R. (2017). Genetic accommodation via modified endocrine signalling explains

phenotypic divergence among spadefoot toad species. *Nature Communications*, *8*(1), 993.

Kumar, S., Suleski, M., Craig, J. M., Kasprowicz, A. E., Sanderford, M., Li, M., Stecher, G., & Hedges, S. B. (2022). TimeTree 5: An expanded resource for species divergence times. *Molecular Biology and Evolution*, *39*(8), msac174. https://doi.org/10.1093/molbev/msac174

Lechner, E. R., Stewart, E. M., Wilson, C. C., & Raby, G. D. (2023). CTmax in brook trout (*Salvelinus fontinalis*) embryos shows an acclimation response to developmental temperatures but is more variable than in later life stages. *Journal of Fish Biology*, *104*, 901–905. https://doi.org/10.1111/jfb.15624

Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S. L., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., … Zommers, Z. (2023). *Climate change 2023: Synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change*. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

Lee, S., Hung, S. S., Fangue, N. A., Haller, L., Verhille, C. E., Zhao, J., & Todgham, A. E. (2016). Effects of feed restriction on the upper temperature tolerance and heat shock response in juvenile green and white sturgeon. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *198*, 87–95. https://doi.org/10.1016/j.cbpa.2016.04.016

Little, A. G., & Seebacher, F. (2015). Temperature determines toxicity: Bisphenol a reduces thermal tolerance in fish. *Environmental Pollution*, *197*, 84–89. https://doi.org/10.1016/j.envpol.2014.12.003

Little, A. G., & Seebacher, F. (2017). Acclimation, acclimatization, and seasonal variation in amphibians and reptiles. In *Amphibian and reptile adaptations to the environment* (pp. 41–62). CRC Press. https://doi.org/10.1201/9781315373638-2

Lutterschmidt, W. I., & Hutchison, V. H. (1997a). The critical thermal maximum: History and critique. *Canadian Journal of Zoology*, *75*(10), 1561–1574. https://doi.org/10.1139/z97-783

Lutterschmidt, W. I., & Hutchison, V. H. (1997b). The critical thermal maximum: Data to support the onset of spasms as the definitive end point. *Canadian Journal of Zoology*, *75*(10), 1553–1560. https://doi.org/10.1139/z97-782

McLaughlin, B. C., Skikne, S. A., Beller, E., Blakey, R. V., Olliff-Yang, R. L., Morueta-Holme, N., Heller, N. E., Brown, B. J., & Zavaleta, E. S. (2022). Conservation strategies for the climate crisis: An update on three decades of biodiversity management recommendations from science. *Biological Conservation*, *268*, 109497. https://doi.org/10.1016/j.biocon.2022.109497

Meek, M. H., Beever, E. A., Barbosa, S., Fitzpatrick, S. W., Fletcher, N. K., Mittan-Moreau, C. S., Reid, B. N., Campbell-Staton, S. C., Green, N. F., & Hellmann, J. J. (2023). Understanding local adaptation to prepare populations for climate change. *Bioscience*, *73*(1), 36–47. https://doi.org/10.1093/biosci/biac101

Mitchell, M., Muftakhidinov, B., Winchen, T., van Schaik, B., & Wilms, A. K. (2021). *Engauge digitizer software*. http://markummitchell.github.io/engauge-digitizer

Mittermeier, R. A., Turner, W. R., Larsen, F. W., Brooks, T. M., & Gascon, C. (2011). Global biodiversity conservation: The critical role of hotspots. In *Biodiversity hotspots: Distribution and protection of conservation priority areas* (pp. 3–22). Springer. https://doi.org/10.1007/978-3-642-20992-5_1

Molina, A. N., Pulgar, J. M., Rezende, E. L., & Carter, M. J. (2023). Heat tolerance of marine ectotherms in a warming Antarctica. *Global Change Biology*, *29*(1), 179–188. https://doi.org/10.1111/gcb.16402

Morgan, R., Andreassen, A. H., Åsheim, E. R., Finnøen, M. H., Dresler, G., Brembu, T., Loh, A., Miest, J. J., & Jutfelt, F. (2022). Reduced physiological plasticity in a fish adapted to stable temperatures. *Proceedings of the National Academy of Sciences of the United States of America*, *119*(22), e2201919119. https://doi.org/10.1073/pnas.2201919119

Morgan, R., Finnøen, M. H., & Jutfelt, F. (2018). CT_{max} is repeatable and doesn't reduce growth in zebrafish. *Scientific Reports*, *8*(1), 7099. https://doi.org/10.1073/pnas.2201919119

Morley, S. A., Peck, L. S., Sunday, J. M., Heiser, S., & Bates, A. E. (2019). Physiological acclimation and persistence of ectothermic species under extreme heat events. *Global Ecology and Biogeography*, *28*(7), 1018–1037. https://doi.org/10.1111/geb.12911

Moyano, M., Candebat, C., Ruhbaum, Y., Alvarez-Fernandez, S., Claireaux, G., Zambonino-Infante, J. L., & Peck, M. A. (2017). Effects of warming rate, acclimation temperature and ontogeny on the critical thermal maximum of temperate marine fish larvae. *PLoS One*, *12*(7), e0179928. https://doi.org/10.1371/journal.pone.0179928

Muñoz, M. M. (2022). The Bogert effect, a factor in evolution. *Evolution*, *76*(s1), 49–66. https://doi.org/10.1111/evo.14388

Navas, C. A., Agudelo-Cantero, G. A., & Loeschcke, V. (2022). Thermal boldness: Volunteer exploration of extreme temperatures in fruit flies. *Journal of Insect Physiology*, *136*, 104330. https://doi.org/10.1016/j.jinsphys.2021.104330

Navas, C. A., Gomes, F. R., & Carvalho, J. E. (2008). Thermal relationships and exercise physiology in anuran amphibians: Integration and evolutionary implications. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *151*(3), 344–362. https://doi.org/10.1016/j.cbpa.2007.07.003

Navas, C. A., & Otani, L. (2007). Physiology, environmental change, and anuran conservation. *Phyllomedusa*. *Journal of Herpetology*, *6*(2), 83–103. https://doi.org/10.11606/issn.2316-9079.v6i2p83-103

Newman, R. A. (1992). Adaptive plasticity in amphibian metamorphosis. *Bioscience*, *42*(9), 671–678. https://doi.org/10.2307/176694

Paradis, E., & Schliep, K. (2019). ape 5.0: An environment for modern phylogenetics and evolutionary analyses in R. *Bioinformatics*, *35*(3), 526–528. https://doi.org/10.1093/bioinformatics/bty633

Peck, L. S., Morley, S. A., Richard, J., & Clark, M. S. (2014). Acclimation and thermal tolerance in Antarctic marine ectotherms. *Journal of Experimental Biology*, *217*(1), 16–22. https://doi.org/10.1242/jeb.089946

Penman, R. J., Bugg, W., Rost-Komiya, B., Earhart, M. L., & Brauner, C. J. (2023). Slow heating rates increase thermal tolerance and alter mRNA HSP expression in juvenile white sturgeon (*Acipenser transmontanus*). *Journal of Thermal Biology*, *115*, 103599. https://doi.org/10.1016/j.jtherbio.2023.103599

Peralta-Maraver, I., & Rezende, E. L. (2021). Heat tolerance in ectotherms scales predictably with body size. *Nature Climate Change*, *11*(1), 58–63. https://doi.org/10.1038/s41558-020-00938-y

Pincebourde, S., Murdock, C. C., Vickers, M., & Sears, M. W. (2016). Fine-scale microclimatic variation can shape the responses of organisms to global change in both natural and urban environments. *Integrative and Comparative Biology*, *56*(1), 45–61. https://doi.org/10.1093/icb/icw016

Pinsky, M. L., Eikeset, A. M., McCauley, D. J., Payne, J. L., & Sunday, J. M. (2019). Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature*, *569*(7754), 108–111. https://doi.org/10.1038/s41586-019-1132-4

Pintanel, P., Tejedo, M., Merino-Viteri, A., Almeida-Reinoso, F., Salinas-Ivanenko, S., López-Rosero, A. C., Llorente, G. A., & Gutiérrez-Pesquera, L. M. (2022). Elevational and local climate variability predicts thermal breadth of mountain tropical tadpoles. *Ecography*, *2022*(5), e05906. https://doi.org/10.1111/ecog.05906

Pörtner, H. (2001). Climate change and temperature-dependent biogeography: Oxygen limitation of thermal tolerance in animals. *Naturwissenschaften*, *88*, 137–146.

Pörtner, H. O. (2002). Climate variations and the physiological basis of temperature dependent biogeography: Systemic to molecular hierarchy of thermal tolerance in animals. *Comparative Biochemistry*

and Physiology Part A: Molecular & Integrative Physiology, *132*(4), 739–761. https://doi.org/10.1016/S1095-6433(02)00045-4

Pörtner, H. O. (2010). Oxygen-and capacity-limitation of thermal tolerance: A matrix for integrating climate-related stressor effects in marine ecosystems. *Journal of Experimental Biology*, *213*(6), 881–893. https://doi.org/10.1242/jeb.037523

Pörtner, H. O., Lucassen, M., & Storch, D. (2005). Metabolic biochemistry: Its role in thermal tolerance and in the capacities of physiological and ecological function. *Fish Physiology*, *22*, 79–154.

Pörtner, H. O., & Peck, M. A. (2010). Climate change effects on fishes and fisheries: Towards a cause-and-effect understanding. *Journal of Fish Biology*, *77*(8), 1745–1779. https://doi.org/10.1111/j.1095-8649.2010.02783.x

Pottier, P., Burke, S., Drobniak, S. M., Lagisz, M., & Nakagawa, S. (2021). Sexual (in) equality? A meta-analysis of sex differences in thermal acclimation capacity across ectotherms. *Functional Ecology*, *35*(12), 2663–2678. https://doi.org/10.1111/1365-2435.13899

Pottier, P., Burke, S., Drobniak, S. M., & Nakagawa, S. (2022). Methodological inconsistencies define thermal bottlenecks in fish life cycle: A comment on Dahlke et al., 2020. *Evolutionary Ecology*, *36*(2), 287–292. https://doi.org/10.1007/s10682-022-10157-w

Pottier, P., Burke, S., Zhang, R. Y., Noble, D. W., Schwanz, L. E., Drobniak, S. M., & Nakagawa, S. (2022). Developmental plasticity in thermal tolerance: Ontogenetic variation, persistence, and future directions. *Ecology Letters*, *25*(10), 2245–2268. https://doi.org/10.1111/ele.14083

Potts, L. B., Mandrak, N. E., & Chapman, L. J. (2021). Coping with climate change: Phenotypic plasticity in an imperilled freshwater fish in response to elevated water temperature. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *31*(10), 2726–2736. https://doi.org/10.1002/aqc.3620

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rohr, J. R., Civitello, D. J., Cohen, J. M., Roznik, E. A., Sinervo, B., & Dell, A. I. (2018). The complex drivers of thermal acclimation and breadth in ectotherms. *Ecology Letters*, *21*(9), 1425–1439. https://doi.org/10.1111/ele.13107

Rohr, J. R., & Palmer, B. D. (2013). Climate change, multiple stressors, and the decline of ectotherms. *Conservation Biology*, *27*(4), 741–751.

Rubalcaba, J. G., & Olalla-Tárraga, M. Á. (2020). The biogeography of thermal risk for terrestrial ectotherms: Scaling of thermal tolerance with body size and latitude. *Journal of Animal Ecology*, *89*(5), 1277–1285. https://doi.org/10.1111/1365-2656.13181

Rudolf, V. H., & Rödel, M. O. (2007). Phenotypic plasticity and optimal timing of metamorphosis under uncertain time constraints. *Evolutionary Ecology*, *21*, 121–142. https://doi.org/10.1007/s10682-006-0017-9

Ruthsatz, K., Dausmann, K. H., Paesler, K., Babos, P., Sabatino, N. M., Peck, M. A., & Glos, J. (2020). Shifts in sensitivity of amphibian metamorphosis to endocrine disruption: The common frog (*Rana temporaria*) as a case study. *Conservation Physiology*, *8*(1), coaa100. https://doi.org/10.1093/conphys/coaa100

Ruthsatz, K., Dausmann, K. H., Peck, M. A., Drees, C., Sabatino, N. M., Becker, L. I., Reese, J., Hartmann, L., & Glos, J. (2018). Thyroid hormone levels and temperature during development alter thermal tolerance and energetics of *Xenopus laevis* larvae. *Conservation Physiology*, *6*(1), coy059. https://doi.org/10.1093/conphys/coy059

Ruthsatz, K., Dausmann, K. H., Peck, M. A., & Glos, J. (2022). Thermal tolerance and acclimation capacity in the European common frog (*Rana temporaria*) change throughout ontogeny. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, *337*(5), 477–490. https://doi.org/10.1002/jez.2582

Ruthsatz, K., Dausmann, K. H., Reinhardt, S., Robinson, T., Sabatino, N. M., Peck, M. A., & Glos, J. (2019). Endocrine disruption alters developmental energy allocation and performance in *Rana temporaria*. *Integrative and Comparative Biology*, *59*(1), 70–88. https://doi.org/10.1093/icb/icz041

Ruthsatz, K., Dausmann, K. H., Reinhardt, S., Robinson, T., Sabatino, N. M., Peck, M. A., & Glos, J. (2020). Post-metamorphic carry-over effects of altered thyroid hormone level and developmental temperature: Physiological plasticity and body condition at two life stages in *Rana temporaria*. *Journal of Comparative Physiology B*, *190*, 297–315. https://doi.org/10.1007/s00360-020-01271-8

Ruthsatz, K., Peck, M. A., Dausmann, K. H., Sabatino, N. M., & Glos, J. (2018). Patterns of temperature induced developmental plasticity in anuran larvae. *Journal of Thermal Biology*, *74*, 123–132. https://doi.org/10.1016/j.jtherbio.2018.03.005

Ruthsatz, K., Rakotoarison, A., Razafimampiandra, J. C., Randriamahefa, V. S., Rabemananjara, F. C., Rakotondraparany, F., Bletz, M. C., & Vences, M. (2022). Field body temperatures in Malagasy rainforest frogs. *Herpetology Notes*, *15*, 565–578.

Schiesari, L., Grillitsch, B., & Grillitsch, H. (2007). Biogeographic biases in research and their consequences for linking amphibian declines to pollution. *Conservation Biology*, *21*(2), 465–471. https://doi.org/10.1111/j.1523-1739.2006.00616.x

Schlichting, C. D., & Pigliucci, M. (1998). *Phenotypic evolution: A reaction norm perspective*. Sinauer Associates Incorporated. https://doi.org/10.1038/sj.hdy.6885352

Seebacher, F., White, C. R., & Franklin, C. E. (2015). Physiological plasticity increases resilience of ectothermic animals to climate change. *Nature Climate Change*, *5*(1), 61–66. https://doi.org/10.1038/nclimate2457

Shah, A. A., Gill, B. A., Encalada, A. C., Flecker, A. S., Funk, W. C., Guayasamin, J. M., Kondratieff, B. C., Poff, N. L., Thomas, S. A., Zamudio, K. R., & Ghalambor, C. K. (2017). Climate variability predicts thermal limits of aquatic insects across elevation and latitude. *Functional Ecology*, *31*(11), 2118–2127. https://doi.org/10.1111/1365-2435.12906

Sherman, E. (1980). Ontogenetic change in thermal tolerance of the toad *Bufo woodhousii fowleri*. *Comparative Biochemistry and Physiology Part A: Physiology*, *65*(2), 227–230. https://doi.org/10.1016/0300-9629(80)90229-7

Shi, Y. B. (2000). *Amphibian metamorphosis: From morphology to molecular biology (No. 19638)*. Wiley-Liss.

Sinai, N., Glos, J., Mohan, A. V., Lyra, M. L., Riepe, M., Thöle, E., Zummach, C., & Ruthsatz, K. (2022). Developmental plasticity in amphibian larvae across the world: Investigating the roles of temperature and latitude. *Journal of Thermal Biology*, *106*, 103233. https://doi.org/10.1016/j.jtherbio.2022.103233

Sinclair, B. J., Marshall, K. E., Sewell, M. A., Levesque, D. L., Willett, C. S., Slotsbo, S., Dong, Y., Harley, C. D. G., Marshall, D. J., Helmuth, B. S., & Huey, R. B. (2016). Can we predict ectotherm responses to climate change using thermal performance curves and body temperatures? *Ecology Letters*, *19*(11), 1372–1385. https://doi.org/10.1111/ele.12686

Somero, G. N. (2005). Linking biogeography to physiology: Evolutionary and acclimatory adjustments of thermal limits. *Frontiers in Zoology*, *2*(1), 1–9. https://doi.org/10.1186/1742-9994-2-1

Somero, G. N. (2010). The physiology of climate change: How potentials for acclimatization and genetic adaptation will determine 'winners' and 'losers'. *Journal of Experimental Biology*, *213*(6), 912–920. https://doi.org/10.1242/jeb.037473

Sørensen, J. G., Kristensen, T. N., & Overgaard, J. (2016). Evolutionary and ecological patterns of thermal acclimation capacity in *Drosophila*: Is it important for keeping up with climate change? *Current Opinion in Insect Science*, *17*, 98–104. https://doi.org/10.1016/j.cois.2016.08.003

Sunday, J. M., Bates, A. E., & Dulvy, N. K. (2011). Global analysis of thermal tolerance and latitude in ectotherms. *Proceedings of the Royal Society B: Biological Sciences*, *278*(1713), 1823–1830.

Sunday, J. M., Bates, A. E., Kearney, M. R., Colwell, R. K., Dulvy, N. K., Longino, J. T., & Huey, R. B. (2014). Thermal-safety margins and the necessity of thermoregulatory behavior across latitude and elevation. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(15), 5610–5615. https://doi.org/10.1073/pnas.1316145111

Sunday, J., Bennett, J. M., Calosi, P., Clusella-Trullas, S., Gravel, S., Hargreaves, A. L., Leiva, F. P., Verberk, W. C. E. P., Olalla-Tárraga, M. Á., & Morales-Castilla, I. (2019). Thermal tolerance patterns across latitude and elevation. *Philosophical Transactions of the Royal Society B*, *374*(1778), 20190036. https://doi.org/10.1098/rstb.2019.0036

Terblanche, J. S., Deere, J. A., Clusella-Trullas, S., Janion, C., & Chown, S. L. (2007). Critical thermal limits depend on methodological context. *Proceedings of the Royal Society B: Biological Sciences*, *274*(1628), 2935–2943. https://doi.org/10.1098/rspb.2007.0985

Tewksbury, J. J., Huey, R. B., & Deutsch, C. A. (2008). Putting the heat on tropical animals. *Science*, *320*(5881), 1296–1297. https://doi.org/10.1126/science.1159328

van der Sleen, P., & Albert, J. S. (2022). Patterns in freshwater fish diversity. In T. Mehner & K. Tockner (Eds.), *Encyclopedia of inland waters* (2nd ed., pp. 243–255). Elsevier. https://doi.org/10.1016/B978-0-12-819166-8.00056-6

van Heerwaarden, B., Kellermann, V., & Sgrò, C. M. (2016). Limited scope for plasticity to increase upper thermal limits. *Functional Ecology*, *30*(12), 1947–1956. https://doi.org/10.1111/1365-2435.12687

van Heerwaarden, B., & Sgrò, C. M. (2021). Male fertility thermal limits predict vulnerability to climate warming. *Nature Communications*, *12*(1), 2214. https://doi.org/10.1038/s41467-021-22546-w

Weaving, H., Terblanche, J. S., Pottier, P., & English, S. (2022). Meta-analysis reveals weak but pervasive plasticity in insect thermal limits. *Nature Communications*, *13*(1), 5292. https://doi.org/10.1038/s41467-022-32953-2

White, C. R., Marshall, D. J., Chown, S. L., Clusella-Trullas, S., Portugal, S. J., Franklin, C. E., & Seebacher, F. (2021). Geographical bias in physiological data limits predictions of global change impacts. *Functional Ecology*, *35*(7), 1572–1578. https://doi.org/10.1111/1365-2435.13807

Wickham, H., & Wickham, H. (2009). Getting started with qplot. In *ggplot2: Elegant graphics for data analysis* (pp. 9–26). Springer. https://doi.org/10.1007/978-3-319-24277-4

Wilbur, H. M. (1980). Complex life cycles. *Annual Review of Ecology and Systematics*, *11*(1), 67–93. https://www.jstor.org/stable/2096903

Winter, M., Fiedler, W., Hochachka, W. M., Koehncke, A., Meiri, S., & De la Riva, I. (2016). Patterns and biases in climate change research on amphibians and reptiles: A systematic review. *Royal Society Open Science*, *3*(9), 160158. https://doi.org/10.1098/rsos.160158

Woodward, G., Perkins, D. M., & Brown, L. E. (2010). Climate change and freshwater ecosystems: Impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society, B: Biological Sciences*, *365*(1549), 2093–2106. https://doi.org/10.1098/rstb.2010.0055

Wu, C. S., & Kam, Y. C. (2005). Thermal tolerance and thermoregulation by Taiwanese rhacophorid tadpoles (*Buergeria japonica*) living in geothermal hot springs and streams. *Herpetologica*, *61*(1), 35–46.

Yu, G., Smith, D. K., Zhu, H., Guan, Y., & Lam, T. T. Y. (2017). ggtree: An R package for visualization and annotation of phylogenetic trees with their covariates and other associated data. *Methods in Ecology and Evolution*, *8*(1), 28–36. https://doi.org/10.1111/2041-210X.12628

Yu, S., Wages, M. R., Cobb, G. P., & Maul, J. D. (2013). Effects of chlorothalonil on development and growth of amphibian embryos and larvae. *Environmental Pollution*, *181*, 329–334. https://doi.org/10.1016/j.envpol.2013.06.017

DATA SOURCES

Bacigalupe, L. D., Gaitán-Espitia, J. D., Barria, A. M., Gonzalez-Mendez, A., Ruiz-Aravena, M., Trinder, M., & Sinervo, B. (2018). Natural selection on plasticity of thermal traits in a highly seasonal environment. *Evolutionary Applications*, *11*(10), 2004–2013. https://doi.org/10.1111/eva.12702

Baduy, F. (2017). *Tolerância ambiental e comportamento social e reprodutivo de Australoheros facetus (Cichlidae): que mecanismos fisiológicos e moleculares permitem a adaptação desta espécie invasora em Portugal?* [PhD dissertation, Universidade do Algarve]. http://hdl.handle.net/10400.1/10768

Baroudy, E., & Elliott, J. M. (1994). The critical thermal limits for juvenile Arctic charr *Salvelinus alpinus*. *Journal of Fish Biology*, *45*(6), 1041–1053. https://doi.org/10.1111/j.1095-8649.1994.tb01071.x

Barrantes, M. E., Lattuca, M. E., Vanella, F. A., & Fernández, D. A. (2017). Thermal ecology of *Galaxias platei* (Pisces, Galaxiidae) in South Patagonia: Perspectives under a climate change scenario. *Hydrobiologia*, *802*, 255–267. https://doi.org/10.1007/s10750-017-3275-3

Barria, A. M., & Bacigalupe, L. D. (2017). Intraspecific geographic variation in thermal limits and acclimatory capacity in a wide distributed endemic frog. *Journal of Thermal Biology*, *69*, 254–260. https://doi.org/10.1016/j.jtherbio.2017.08.010

Becker, C. D., & Genoway, R. G. (1979b). Evaluation of the critical thermal maximum for determining thermal tolerance of freshwater fish. *Environmental Biology of Fishes*, *4*, 245–256. https://doi.org/10.1007/BF00005481

Bennett, W. A., & Beitinger, T. L. (1997). Temperature tolerance of the sheepshead minnow, *Cyprinodon variegatus*. *Copeia*, *1997*, 77–87. https://doi.org/10.2307/1447842

Billman, E. J., Wagner, E. J., Arndt, R. E., & VanDyke, E. (2008). Optimal temperatures for growth and upper thermal tolerance of juvenile northern leatherside chub. *Western North American Naturalist*, *68*(4), 463–474. https://doi.org/10.3398/1527-0904-68.4.463

Bonar, S. A., Carveth, C. J., Widmer, A. M., & Simms, J. (2005). *Upper temperature tolerance of loach minnow and spikedace under acute, chronic, and fluctuating thermal regimes*. Fisheries research report (04-05). https://doi.org/10.1577/T04-205.1

Brattstrom, B. H. (1968). Thermal acclimation in anuran amphibians as a function of latitude and altitude. *Comparative Biochemistry and Physiology*, *24*(1), 93–111. https://doi.org/10.1016/0010-406X(68)90961-4

Brattstrom, B. H. (1970). Thermal acclimation in Australian amphibians. *Comparative Biochemistry and Physiology*, *35*(1), 69–103. https://doi.org/10.1016/0010-406X(70)90915-1

Brewer, S. K., Mollenhauer, R., Alexander, J., & Moore, D. (2022). Critical thermal maximum values for stream fishes, including distinct populations of smallmouth bass. *North American Journal of Fisheries Management*, *42*(2), 352–360. https://doi.org/10.1002/nafm.10749

Chagnon, N., & Hlohowskyj, I. (1989). Effects of phenol exposure on the thermal tolerance ability of the central stoneroller minnow. *Bulletin of Environmental Contamination and Toxicology*, *42*, 614–619. https://www.academia.edu/17432545/Effects_of_phenol_exposure_on_the_thermal_tolerance_ability_of_the_central_stoneroller_minnow

Chen, T. C., Kam, Y. C., & Lin, Y. S. (2001). Thermal physiology and reproductive phenology of *Buergeria japonica* (Rhacophoridae) breeding in a stream and a geothermal hotspring in Taiwan. *Zoological Science*, *18*(4), 591–596. https://doi.org/10.2108/zsj.18.591

Chrétien, E., & Chapman, L. J. (2016). Tropical fish in a warming world: Thermal tolerance of Nile perch *Lates niloticus* (L.) in Lake Nabugabo, Uganda. *Conservation Physiology*, *4*(1), cow062. https://doi.org/10.1093/conphys/cow062

Christian, K. A., Nunez, F., Clos, L., & Diaz, L. (1988). Thermal relations of some tropical frogs along an altitudinal gradient. *Biotropica*, *20*(3), 236–239. https://doi.org/10.2307/2388239

Chung, K., & Méndez, S. (2010). Tolerancia térmica comparativa en algunos peces tropicales de Venezuela. *Universidad del Zulia*, *1*(1), 1–7. https://produccioncientificaluz.org/index.php/ciencia/article/view/8665

Chung, K. S. (2001). Critical thermal maxima and acclimation rate of the tropical guppy *Poecilla reticulata*. *Hydrobiologia*, *462*, 253–257. https://doi.org/10.1023/A:1013158904036

Claussen, D. L. (1973). The thermal relations of the tailed frog, *Ascaphus truei*, and the Pacific treefrog, *Hyla regilla*. *Comparative Biochemistry and Physiology Part A: Physiology*, *44*(1), 137–153. https://doi.org/10.1016/0300-9629(73)90377-0

Claussen, D. L. (1977b). Thermal acclimation in ambystomatid salamanders. *Comparative Biochemistry and Physiology Part A: Physiology*, *58*(4), 333–340. https://doi.org/10.1016/0300-9629(77)90150-5

Cortemeglia, C., & Beitinger, T. L. (2008). Temperature tolerance of green sunfish (*Lepomis cyanellus*). *The Texas Journal of Science*, *60*(3), 179–189.

Culumber, Z. W., & Monks, S. (2014). Resilience to extreme temperature events: Acclimation capacity and body condition of a polymorphic fish in response to thermal stress. *Biological Journal of the Linnean Society*, *111*(3), 504–510. https://doi.org/10.1111/bij.12230

Cupp, P. V., Jr. (1980). Thermal tolerance of five salientian amphibians during development and metamorphosis. *Herpetologica*, *36*(3), 234–244. https://www.jstor.org/stable/3891820

Darveau, C. A., Taylor, E. B., & Schulte, P. M. (2012). Thermal physiology of warm-spring colonists: Variation among lake chub (Cyprinidae: *Couesius plumbeus*) populations. *Physiological and Biochemical Zoology*, *85*(6), 607–617. https://doi.org/10.1086/665539

Davies, S. J., McGeoch, M. A., & Clusella-Trullas, S. (2015). Plasticity of thermal tolerance and metabolism but not water loss in an invasive reed frog. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *189*, 11–20. https://doi.org/10.1016/j.cbpa.2015.06.033

Deacon, J. E., Schumann, P. B., & Stuenkel, E. L. (1987). Thermal tolerances and preferences of fishes of the Virgin River system (Utah, Arizona, Nevada). *The Great Basin Naturalist*, *47*, 538–546. https://www.jstor.org/stable/41712368

Drown, M. K., DeLiberto, A. N., Ehrlich, M. A., Crawford, D. L., & Oleksiak, M. F. (2021). Interindividual plasticity in metabolic and thermal tolerance traits from populations subjected to recent anthropogenic heating. *Royal Society Open Science*, *8*(7), 210440. https://doi.org/10.1098/rsos.210440

Dunlap, D. G. (1968). Critical thermal maximum as a function of temperature of acclimation in two species of hylid frogs. *Physiological Zoology*, *41*(4), 432–439. https://doi.org/10.1086/physzool.41.4.30155478

Elliott, J. M., & Elliott, J. A. (1995). The critical thermal limits for the bullhead, *Cottus gobio*, from three populations in north-west England. *Freshwater Biology*, *33*(3), 411–418. https://doi.org/10.1111/j.1365-2427.1995.tb00403.x

Elliott, J. M., & Klemetsen, A. (2002). The upper critical thermal limits for alevins of Arctic charr from a Norwegian lake north of the Arctic circle. *Journal of Fish Biology*, *60*(5), 1338–1341. https://doi.org/10.1111/j.1095-8649.2002.tb01727.x

Elwood, J. R. L. (2003). *Variation in hsp70 levels and thermotolerance among terrestrial salamanders of the Plethodon glutinosus complex* [ProQuest dissertations, Drexel University]. https://www.proquest.com/openview/2ba97055ce26610e6f21f60723458c20

Enriquez-Urzelai, U., Sacco, M., Palacio, A. S., Pintanel, P., Tejedo, M., & Nicieza, A. G. (2019b). Ontogenetic reduction in thermal tolerance is not alleviated by earlier developmental acclimation in *Rana temporaria*. *Oecologia*, *189*, 385–394. https://doi.org/10.1007/s00442-019-04342-y

Enriquez-Urzelai, U., Tingley, R., Kearney, M. R., Sacco, M., Palacio, A. S., Tejedo, M., & Nicieza, A. G. (2020b). The roles of acclimation and behaviour in buffering climate change impacts along elevational gradients. *Journal of Animal Ecology*, *89*(7), 1722–1734. https://doi.org/10.1111/1365-2656.13222

Fan, X. L., Lin, Z. H., & Scheffers, B. R. (2021). Physiological, developmental, and behavioral plasticity in response to thermal acclimation. *Journal of Thermal Biology*, *97*, 102866. https://doi.org/10.1016/j.jtherbio.2021.102866

Fangue, N. A., Hofmeister, M., & Schulte, P. M. (2006). Intraspecific variation in thermal tolerance and heat shock protein gene expression in common killifish, *Fundulus heteroclitus*. *Journal of Experimental Biology*, *209*(15), 2859–2872. https://doi.org/10.1242/jeb.02260

Fries, J. N., & Gibson, J. R. (2010). Critical thermal maxima of captive-bred Devils River minnows (*Dionda diaboli*). *The Southwestern Naturalist*, *55*(4), 544–550. https://doi.org/10.1894/RJE-02.1

Gómez, S. E. (2014). Máximo térmico crítico en peces argentinos de agua dulce, Sudamérica. *Revista del Museo Argentino de Ciencias Naturales*, *16*(2), 123–127. http://www.scielo.org.ar/scielo.php?pid=S185304002014000200004%26script=sci_abstract%26tlng=e

Gvoždík, L., Puky, M., & Šugerková, M. (2007). Acclimation is beneficial at extreme test temperatures in the Danube crested newt, *Triturus dobrogicus* (Caudata, Salamandridae). *Biological Journal of the Linnean Society*, *90*(4), 627–636. https://doi.org/10.1111/j.1095-8312.2006.00752.x

Heath, W. G. (1963). Thermoperiodism in sea-run cutthroat trout (*Salmo clarki clarki*). *Science*, *142*(3591), 486–488. https://doi.org/10.1126/science.142.3591.486

Hernández-Rordiguez, M., & Bückle-Ramirez, L. F. (2002). Temperature tolerance polygon of *Poecilia sphenops* Valenciennes (Pisces: Poeciliidae). *Journal of Thermal Biology*, *27*(1), 1–5. https://doi.org/10.1016/S0306-4565(01)00008-0

Hlohowskyj, I., & Wissing, T. E. (1985). Seasonal changes in the critical thermal maxima of fantail (*Etheostoma flabellare*), greenside (*Etheostoma blennioides*), and rainbow (*Etheostoma caeruleum*) darters. *Canadian Journal of Zoology*, *63*(7), 1629–1633. https://doi.org/10.1139/z85-241

Hofmann, N., & Fischer, P. (2002). Temperature preferences and critical thermal limits of burbot: Implications for habitat selection and ontogenetic habitat shift. *Transactions of the American Fisheries Society*, *131*(6), 1164–1172. https://doi.org/10.1577/1548-8659(2002)131%3C1164:TPACTL%3E2.0.CO;2

Holland, W. E., Smith, M. H., Gibbons, J. W., & Brown, D. H. (1974). Thermal tolerances of fish from a reservoir receiving heated effluent from a nuclear reactor. *Physiological Zoology*, *47*(2), 110–118. https://doi.org/10.1086/physzool.47.2.30155628

Holzman, N., & McManus, J. J. (1973). Effects of acclimation on metabolic rate and thermal tolerance in the carpenter frog, *Rana vergatipes*. *Comparative Biochemistry and Physiology Part A: Physiology*, *45*(3), 833–842. https://doi.org/10.1016/0300-9629(73)90086-8

Howard, J. H., Wallace, R. L., & Stauffer, J. R. (1983). Critical thermal maxima in populations of *Ambystoma macrodactylum* from different elevations. *Journal of Herpetology*, *17*(4), 400–402. https://doi.org/10.2307/1563592

Hutchison, V. H. (1961b). Critical thermal maxima in salamanders. *Physiological Zoology*, *34*(2), 92–125. https://doi.org/10.1086/physzool.34.2.30152688

Hutchison, V. H., & Rowlan, S. D. (1975). Thermal acclimation and tolerance in the mudpuppy, *Necturus maculosus*. *Journal of Herpetology*, *9*(4), 367–368. https://doi.org/10.2307/1562944

Johnson, C. R. (1972). Diel variation in the thermal tolerance of *Litoria gracilenta* (Anura: Hylidae). *Comparative Biochemistry and Physiology Part A: Physiology*, *41*(4), 727–730. https://doi.org/10.1016/0300-9629(72)90337-4

Jung, E. H., Brix, K. V., Richards, J. G., Val, A. L., & Brauner, C. J. (2020). Reduced hypoxia tolerance and survival at elevated temperatures may limit the ability of Amazonian fishes to survive in a warming world. *Science of the Total Environment*, *748*, 141349. https://doi.org/10.1016/j.scitotenv.2020.141349

Kaya, C. M., Brussard, P. F., Cameron, D. G., & Vyse, E. R. (1992). Biochemical genetics and thermal tolerances of Kendall Warm Springs dace (*Rhinichthys osculus thermalis*) and Green River speckled dace (*R. o. yarrowi*). *Copeia*, *1992*(2), 528–535. https://doi.org/10.2307/1446213

Kelly, N. I., Burness, G., McDermid, J. L., & Wilson, C. C. (2014). Ice age fish in a warming world: Minimal variation in thermal acclimation capacity among lake trout (*Salvelinus namaycush*) populations. *Conservation. Physiology*, *2*(1), cou025. https://doi.org/10.1093/conphys/cou025

Koehle, J. J., & Adelman, I. R. (2007). The effects of temperature, dissolved oxygen, and Asian tapeworm infection on growth and survival of the *Topeka shiner*. *Transactions of the American Fisheries Society*, *136*(6), 1607–1613. https://doi.org/10.1577/T07-033.1

Komoroske, L. M., Connon, R. E., Lindberg, J., Cheng, B. S., Castillo, G., Hasenbein, M., & Fangue, N. A. (2014). Ontogeny influences sensitivity to climate change stressors in an endangered fish. *Conservation Physiology*, *2*(1), cou008. https://doi.org/10.1093/conphys/cou008

Lattuca, M. E., Boy, C. C., Vanella, F. A., Barrantes, M. E., & Fernández, D. A. (2018). Thermal responses of three native fishes from estuarine areas of the Beagle Channel, and their implications for climate change. *Hydrobiologia*, *808*, 235–249. https://doi.org/10.1007/s10750-017-3424-810.1007/s10750-017-3424-8

Layne, J. R., Jr., & Claussen, D. L. (1982). Seasonal variation in the thermal acclimation of critical thermal maxima (CTMax) and minima (CTMin) in the salamander *Eurycea bislineata*. *Journal of Thermal Biology*, *7*(1), 29–33. https://doi.org/10.1016/0306-4565(82)90016-X

Lee, R. M., & Rinne, J. N. (1980). Critical thermal maxima of five trout species in the southwestern United States. *Transactions of the American Fisheries Society*, *109*(6), 632–635. https://doi.org/10.1577/1548-8659(1980)109<632:CTMOFT>2.0.CO;2

Lohr, S. C., Byorth, P. A., Kaya, C. M., & Dwyer, W. P. (1996). High-temperature tolerances of fluvial Arctic grayling and comparisons with summer river temperatures of the Big Hole River, Montana. *Transactions of the American Fisheries Society*, *125*(6), 933–939. https://doi.org/10.1577/1548-8659(1996)125<0933:HTTOFA>2.3.CO;2

Lotshaw, D. P. (1977). Temperature adaptation and effects of thermal acclimation in *Rana sylvatica* and *Rana catesbeiana*. *Comparative Biochemistry and Physiology Part A: Physiology*, *56*(3), 287–294. https://doi.org/10.1016/0300-9629(77)90239-0

Lu, H. L., Wu, Q., Geng, J., & Dang, W. (2016). Swimming performance and thermal resistance of juvenile and adult newts acclimated to different temperatures. *Acta Herpetologica*, *11*(2), 189–195. https://doi.org/10.13128/Acta_Herpetol-18616

Majhi, S. K., & Das, S. K. (2013). Thermal tolerance, oxygen consumption and stress response in *Danio dangila* and *Brachydanio rerio* (Hamilton, 1822) acclimated to four temperatures. *Turkish Journal of Fisheries and Aquatic Sciences*, *13*(2), 359–365. https://doi.org/10.4194/1303-2712-v13_2_19

Martínez, J. D., Cadena, C. D., & Torres, M. (2016). Critical thermal limits of *Poecilia caucana* (Steindachner, 1880) (Cyprinodontiformes: Poeciliidae). *Neotropical Ichthyology*, *14*, e150171. https://doi.org/10.1590/1982-0224-20150171

McDonnell, L. (2014). *Effects of elevated temperature on metabolic performance and thermal tolerance of a widespread African cichlid* [Master of Science thesis, McGill University]. https://www.proquest.com/openview/9bf88cf4184cdc8e007382e221a92b0b/1?pq-origsite=gscholar&cbl=18750&diss=y

Menke, M. E., & Claussen, D. L. (1982). Thermal acclimation and hardening in tadpoles of the bullfrog, *Rana catesbeiana*. *Journal of Thermal Biology*, *7*(4), 215–219. https://doi.org/10.1016/0306-4565(82)90027-4

Messaad, I. A., Peters, E. J., & Young, L. (2000). Thermal tolerance of red shiner (*Cyprinella lutrensis*) after exposure to atrazine, terbufos, and their mixtures. *Bulletin of Environmental Contamination and Toxicology*, *64*(5), 748–754. https://doi.org/10.1007/s001280000067

Mueller, C. A., Bucsky, J., Korito, L., & Manzanares, S. (2019). Immediate and persistent effects of temperature on oxygen consumption and thermal tolerance in embryos and larvae of the Baja California chorus frog, *Pseudacris hypochondriaca*. *Frontiers in Physiology*, *10*, 754. https://doi.org/10.3389/fphys.2019.00754

Nelson, J. A., Rieger, K. J., Gruber, D., Cutler, M., Buckner, B., & Oufiero, C. E. (2021). Thermal tolerance of cyprinids along an urban-rural gradient: Plasticity, repeatability and effects of swimming and temperature shock. *Journal of Thermal Biology*, *100*, 103047. https://doi.org/10.1016/j.jtherbio.2021.103047

Neto, F. S. (2010). *Avaliação da tolerância térmica de Corydoras ehrhardti e Scleromystax barbatus (Siluriformes: Callichthyidae) peixes endêmicos na Floresta Atlântica Paranaense, como subsídio para conservação das espécies em tempos de aquecimento global* [Bachelor thesis, Universidade Federal do Paraná]. https://acervodigital.ufpr.br/bitstream/handle/1884/30680/Monografia%20Felipe%20Skora%20Neto.pdf?sequence=1

Noland, R., & Ultsch, G. R. (1981). The roles of temperature and dissolved oxygen in microhabitat selection by the tadpoles of a frog (*Rana pipiens*) and a toad (*Bufo terrestris*). *Copeia*, *1981*, 645–652. https://doi.org/10.2307/1444570

Novinger, D. C., & Coon, T. G. (2000). Behavior and physiology of the redside dace, *Clinostomus elongatus*, a threatened species in Michigan. *Environmental Biology of Fishes*, *57*, 315–326. https://doi.org/10.1023/A:1007526414384

Nyboer, E. A., Chretien, E., & Chapman, L. J. (2020). Divergence in aerobic scope and thermal tolerance is related to local thermal regime in two populations of introduced Nile perch (*Lates niloticus*). *Journal of Fish Biology*, *97*(1), 231–245. https://doi.org/10.1111/jfb.14355

Ortubay, S. G., Gómez, S. E., & Cussac, V. E. (1997). Lethal temperatures of a Neotropical fish relic in Patagonia, the scale-less characinid *Gymnocharacinus bergi*. *Environmental Biology of Fishes*, *49*, 341–350. https://doi.org/10.1023/A:1007317602738

Ostrand, K. G., & Wilde, G. R. (2001). Temperature, dissolved oxygen, and salinity tolerances of five prairie stream fishes and their role in explaining fish assemblage patterns. *Transactions of the American Fisheries Society*, *130*(5), 742–749. https://doi.org/10.1577/1548-8659(2001)130<0742:TDOAST>2.0.CO;2

Otto, R. G. (1973). Temperature tolerance of the mosquitofish, *Gambmia affinis* (Baird and Girard). *Journal of Fish Biology*, *5*(5), 575–585. https://doi.org/10.1111/j.1095-8649.1973.tb04490.x

Otto, R. G., & Rice, J. O. H. (1977). Responses of a freshwater sculpin (*Cottus cognatus gracilis*) to temperature. *Transactions of the American Fisheries Society*, *106*(1), 89–94. https://doi.org/10.1577/1548-8659(1977)106<89:ROAFSC>2.0.CO;2

Oyamaguchi, H. M., Vo, P., Grewal, K., Do, R., Erwin, E., Jeong, N., Tse, K., Chen, C., Miyake, M., Lin, A., & Gridi-Papp, M. (2018b). Thermal sensitivity of a Neotropical amphibian (*Engystomops pustulosus*) and its vulnerability to climate change. *Biotropica*, *50*(2), 326–337. https://doi.org/10.1111/btp.12519

Penny, F. M., & Pavey, S. A. (2021). Increased acute thermal tolerance and little change to hematology following acclimation to warm water in juvenile Striped Bass, *Morone saxatilis*. *Environmental Biology of Fishes*, *104*, 489–500. https://doi.org/10.1007/s10641-021-01088-6

Philippe, C., Hautekiet, P., Grégoir, A. F., Thoré, E. S., Brendonck, L., De Boeck, G., & Pinceel, T. (2019). Interactive effects of 3, 4-DCA and temperature on the annual killifish *Nothobranchius furzeri*. *Aquatic Toxicology*, *212*, 146–153. https://doi.org/10.1016/j.aquatox.2019.05.009

Philippe, C., Hautekiet, P., Grégoir, A. F., Thoré, E. S., Pinceel, T., Stoks, R., Brendonck, L., & Boeck, G. D. (2018). Combined effects of cadmium exposure and temperature on the annual killifish (*Nothobranchius furzeri*). *Environmental Toxicology and Chemistry*, *37*(9), 2361–2371. https://doi.org/10.1002/etc.4182

Robert Feldmeth, C., Stone, E. A., & Brown, J. H. (1974). An increased scope for thermal tolerance upon acclimating pupfish (*Cyprinodon*) to cycling temperatures. *Journal of Comparative Physiology*, *89*(1), 39–44. https://doi.org/10.1007/BF00696161

Ruthsatz, K., Dausmann, K. H., Peck, M. A., & Glos, J. (2022). Thermal tolerance and acclimation capacity in the European common frog (*Rana temporaria*) change throughout ontogeny. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, *337*(5), 477–490. https://doi.org/10.1002/jez.2582

Ruthsatz, K., Dausmann, K. H., Reinhardt, S., Robinson, T., Sabatino, N. M., Peck, M. A., & Glos, J. (2020). Post-metamorphic carry-over effects of altered thyroid hormone level and developmental temperature: Physiological plasticity and body condition at two life stages in *Rana temporaria*. *Journal of Comparative Physiology B*, *190*, 297–315. https://doi.org/10.1007/s00360-020-01271-8

Schultz, L. D., & Bertrand, K. N. (2011). An assessment of the lethal thermal maxima for mountain sucker. *Western North American Naturalist*, *71*(3), 404–411. https://doi.org/10.3398/064.071.0308

Sealander, J. A. (1969). Critical thermal maxima of some Arkansas salamanders in relation to thermal acclimation. *Herpetologica*, *25*(2), 122–124. https://www.jstor.org/stable/3890956

Simon, M. N., Ribeiro, P. L., & Navas, C. A. (2015). Upper thermal tolerance plasticity in tropical amphibian species from contrasting habitats: Implications for warming impact prediction. *Journal of Thermal Biology*, *48*, 36–44. https://doi.org/10.1016/j.jtherbio.2014.12.008

Simons, M. (1984). *Species specific responses of freshwater organisms to elevated water temperatures*. Waikato Valley Authority. Technical publication 29. https://docs.niwa.co.nz/library/public/WVAtp29.pdf

Smith, R. K., & Fausch, K. D. (1997). Thermal tolerance and vegetation preference of Arkansas darter and Johnny darter from Colorado plains streams. *Transactions of the American Fisheries Society*, *126*(4), 676–686. https://doi.org/10.1577/1548-8659(1997)126<0676:TTAVPO>2.3.CO;2

Spotila, J. R. (1972). Role of temperature and water in the ecology of lungless salamanders. *Ecological Monographs*, *42*(1), 95–125. https://doi.org/10.2307/1942232

Thompson, L. C., Fangue, N. A., Cech, J. J., Jr., Cocherell, D. E., & Kaufman, R. C. (2012). *Juvenile and adult hardhead thermal tolerances and preferences: Temperature preference, critical thermal limits, active and resting metabolism, and blood-oxygen equilibria*. Center for Aquatic Biology and Aquaculture technical report. https://ucanr.edu/sites/Thompsonlab/files/174435.pdf

Walsh, S. J., Haney, D. C., & Timmerman, C. M. (1997). Variation in thermal tolerance and routine metabolism among spring-and stream dwelling freshwater sculpins (Teleostei: Cottidae) of the southeastern United States. *Ecology of Freshwater Fish*, *6*(2), 84–94. https://doi.org/10.1111/j.1600-0633.1997.tb00148.x

Walsh, S. J., Haney, D. C., Timmerman, C. M., & Dorazio, R. M. (1998). Physiological tolerances of juvenile robust redhorse, *Moxostoma robustum*: Conservation implications for an imperiled species. *Environmental Biology of Fishes*, *51*, 429–444. https://doi.org/10.1023/A:1007486632102

Young, P. S., & Cech, J. J., Jr. (1996). Environmental tolerances and requirements of splittail. *Transactions of the American Fisheries Society*, *125*(5), 664–678. https://doi.org/10.1577/1548-8659(1996)125<0664:ETAROS>2.3.CO;2

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Ruthsatz, K., Dahlke, F., Alter, K., Wohlrab, S., Eterovick, P. C., Lyra, M. L., Gippner, S., Cooke, S. J., & Peck, M. A. (2024). Acclimation capacity to global warming of amphibians and freshwater fishes: Drivers, patterns, and data limitations. *Global Change Biology*, *30*, e17318. https://doi.org/10.1111/gcb.17318