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Hottest year in recorded history compounds global biodiversity risks

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As climate change accelerates, effectively monitoring and managing the growing impacts on biodiversity is an urgent priority. Here, we identify the exposure of species to unprecedented heat to evaluate the potential impact of 2024—the hottest year on record—across >33,000 vertebrate species worldwide. One in six (5,368) species were exposed to unprecedented temperatures across >25% of their range—68% more species than in 2023. Most (81%) species exposed in 2023 were also exposed in 2024, potentially compounding risks. For the first time, widespread species were exposed to extreme temperatures across >10% of their ranges. We propose using these exposure estimates to inform monitoring and mitigation efforts to avoid the worst impacts of climate change.

thermal exposure | extreme climate | early warning | 2024 | extinction debts

Extreme weather caused by anthropogenic climate change poses a novel risk to species. Without mitigation, up to a third of species could be committed to extinction by 2100 (1). However, most efforts to prevent biodiversity declines under climate change have focused on long-term predictions spanning decades (1, 2). Although such forecasts are essential for long-term policymaking, near-term hindcasts and forecasts are needed to guide monitoring for impacts because species can experience severe declines following just one year of extreme weather (3). For example, howler monkey populations declined due to drought and heat in Mexico in 2024 (4), and 595 Australian endemic plant species became threatened by drought-induced fires in 2019 (5). Rapid assessments of recent risks from extreme climate are needed now more than ever to pinpoint where emergency monitoring or mitigation are immediately required.

Here, we quantify exposure to historically unprecedented annual heat for all terrestrial vertebrates in 2024, the hottest year on record to date (6). We focused on thermal exposure given temperature's crucial role in shaping metabolic rates, life history transitions, phenology, behavior, physiology, and species interactions (7). We define a thermal exposure event whenever local mean annual temperatures exceed the maximum recorded temperature that each species has experienced across its range and over time (1940–2023; hereafter thermal history). We focus solely on exposure and not sensitivity and adaptability [e.g., climate change vulnerability analysis; Foden et al. (8)] because comprehensive global data on species' sensitivity and adaptability are generally unavailable (9). Our exposure estimates might underestimate risk if species are locally adapted or respond to factors besides temperature, while they may overestimate risk if they can retreat to microclimatic refugia. However, we propose that thermal exposure provides a first step toward developing a species-specific, transparent, and globally applicable tool for estimating potential weather risks to biodiversity (9) and prioritizing monitoring to determine species responses.

For each species, we identified where 2024 conditions exceeded its thermal history. We summed these 2024 exposure events over species in each quarter degree pixel (hereafter "assemblage exposure") and tested whether assemblage exposure was higher with:

H1. High magnitude of warming, likely exceeding historical extremes.

H2. Low historical temporal variation, where many species are not adapted to variable temperatures.

H3. Both (1) and (2), where only the greatest magnitude of warming might exceed historical temporal variation.

H4. Many species with small ranges, because these likely sample little thermal variation and might not adapt to more extreme temperatures.

H5. Low spatial variation in temperatures, thus extending H4 to account for wider ranges in homogeneous areas.

H6. High species richness because more diverse places have more species to potentially experience exposure.

H7. High past assemblage exposure, e.g., in 2023, if atmospheric processes remain consistent through time, and the same locations frequently experience new extremes.

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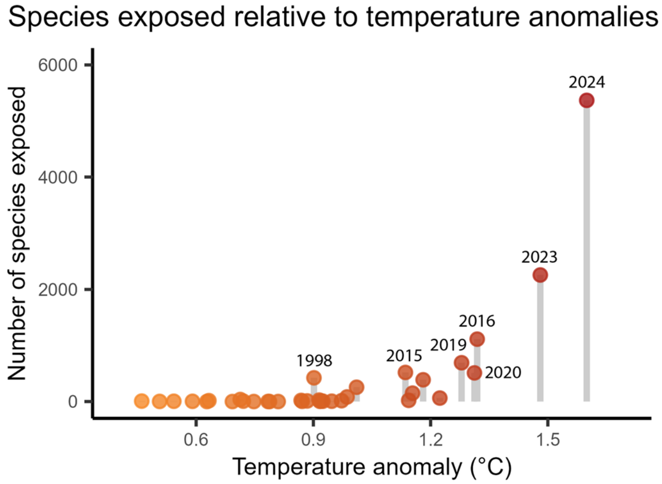

Fig. 1. The number of terrestrial vertebrate species highly thermally exposed (>25% range) over time versus the mean global terrestrial temperature anomaly (denoted by color scale of points). In 2023, ~1 in 10 vertebrate species were highly exposed thermally, increasing to ~1 in 6 species in 2024. Notably, the seven worst years have all occurred in the last decade.

Exposure Threats Are Compounding Across Species, Time, and Space

Overall Patterns. In 2024, 15.9% (5,368 species) of terrestrial vertebrates were exposed to unprecedented heat across >25% of their range (hereafter "highly exposed"; Fig. 1). Nearly two and a half times more species were exposed than in the previous warmest year, 2023. This increase is particularly worrisome because many species had already experienced high heat exposure in 2023—twice as many as in 2016, the last warmest year. In 2024, 20% of the land surface contained one or more exposed species (17% in 2023), while >20 exposed species occurred across 2.0% (1.3% in 2023) of the land surface. Highly exposed species were distributed across taxonomic groups similarly to 2023 (30% of amphibians, 21% of reptiles, 11% of mammals, and 6% of birds) (10). Not only were more species exposed in 2024, but this exposure occurred over larger proportions of their range, with the mean increasing from 17.6 to 21% (Fig. 2).

Of the 847 ecoregions defined by ref. 11, 51% had at least one highly exposed species, increasing from 45% in 2023 (10). Tropical moist broadleaf forests were disproportionately exposed, with 197 constituent ecoregions affected, followed by xeric shrublands (42 ecoregions) and sub/tropical grasslands (40 ecoregions). Nine of the 10 ecoregions with the most highly exposed species were Neotropical, with the most exposure in the Southwest Amazon moist forests (170 species), Peruvian Yungas (166 species), Eastern Cordillera Real montane forests (140 species), and the Ucayali moist forests (140 species).

Hypotheses. In 2024, 36% of the land surface was warmer than the 0.99 quantile of the historical record in that pixel, while 25% was the warmest in the entire record. Warming magnitude (H1) explained 8% of the variation in assemblage exposure. However, many places experienced locally extreme heat without species exposure because they experience these temperatures elsewhere in their range (24% of land). Low historical temperature variation (H2) similarly explained 8% of variation in assemblage exposure, while combining variation with warming magnitude and their interaction (H3) explained 14% of exposure variation.

We also expected that small-ranged species (<20,000 km^2) would inhabit more homogeneous environments (H4) and thus would be more exposed. As expected, 91% of the species highly exposed in 2024 had small ranges. However, this explanation did not extend to full assemblages: local rarity (median of 1/range size) explained 0% of assemblage exposure. The disparity in explanations underlying species- versus assemblage-exposure occurs due to the co-occurrence of species with heterogeneous niches. Although most exposed species have small ranges, most small-ranged species are not exposed, and thus assemblage exposure is not predicted well by community-level rarity.

We expected more exposure where species assemblages generally experience low spatial variation in temperature across their respective ranges (H5), but this factor only explained 5% of the variation. However, individual species that experienced low thermal variation were somewhat more likely to be exposed, with species-specific thermal ranges explaining 18% of the variation in the proportional range exposed.

More exposed species occurred in places with higher species richness (H6), but this effect only explained 6% of the variation. In contrast, assemblage exposure in 2023 (H7) was the strongest predictor of 2024 exposure, explaining 55% of the variation. 81% of the 3,188 species highly exposed in 2023 were again exposed in 2024. Repeated exposure is a proxy for the realized combinations of other mechanisms in H1-6 and common atmospheric processes across years that explain exposure patterns. A full model including all covariates/hypotheses explained 60% of the variation in assemblage exposure, but this explanation was driven largely by 2023 exposure (dropping to 15% if 2023 exposure was removed). Overall, results suggest that exposure is not random and has been concentrated in certain regions and for certain species.

Conclusions

Using a transparent and intuitive estimate, we found that one in six (15.9%) vertebrate species were exposed to extreme heat in 2024. For half of them, this was the second extreme exposure in two years. This increase in heat exposure is alarming because compounded fitness reductions over time (12) likely elevate risk (13). Even when immediate declines are not observed, these demographic consequences could drive extinction debts to be realized years later (14).

Most exposure occurred in the Tropics, although most of the Tropical species were not exposed, which leads to the relatively low explanatory power of our hypotheses. 85% of highly exposed species were found exclusively in the Tropics, where low interannual variability, small ranges, and high species richness combine to increase threats. Although the absolute magnitude of climate change is lowest in the Tropics, they are most likely to experience no-analogue climates (15) because no hotter places exist nearby for them to have experienced these conditions. Therefore, tropical species either need to adapt or die, whereas temperate species are generally wide-ranging, experience and tolerate broader temperatures, and could move to nearby regions with cooler temperatures. Despite these general trends, considerable variation remains that reflects the idiosyncrasies of species niches and available habitat, making exposure a potentially valuable metric that synthesizes multiple processes by connecting the magnitude of current climate extremes to species' vulnerabilities based on thermal histories in space and time.

In 2024, species with large ranges (>median range size = 103,777 km^2; roughly the size of Cuba) were exposed for the first time. Though 2023 shattered previous exposure records (10), no wide-ranging species were exposed across >10% of their range, while in 2024 this number jumped to 676 species. Exposure to

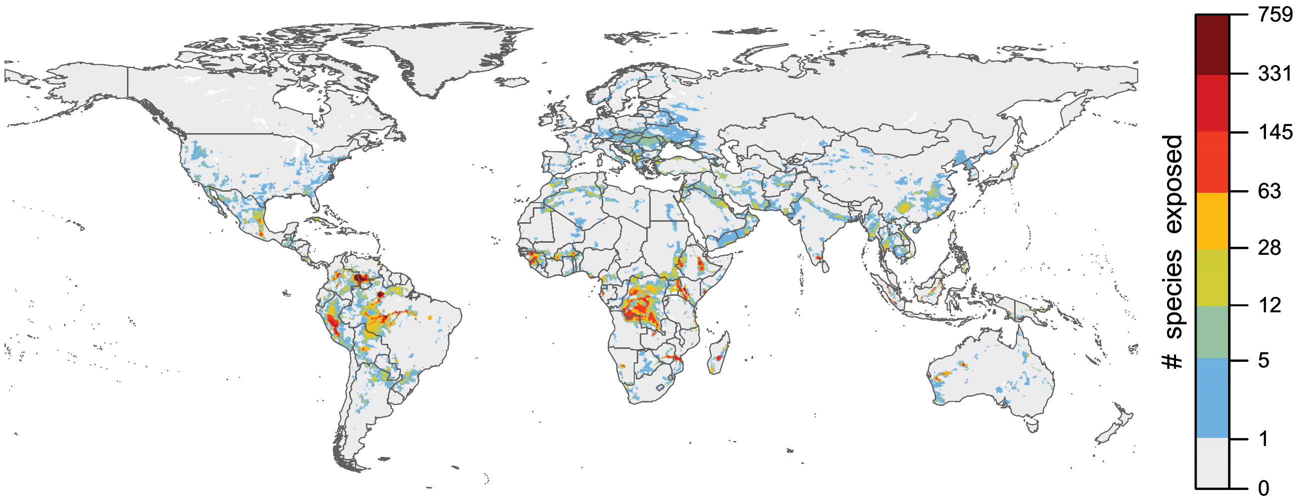

Fig. 2. The number of terrestrial vertebrate species exposed to extreme mean annual temperatures beyond their thermal history limits. The highest assemblage exposure occurred in the tropics, particularly in moist broadleaf forests, but considerable variation among regions is evident.

wide-ranging species is particularly concerning because they may contribute substantially to ecosystem functioning.

Mapping exposure to unprecedented temperatures is just the first step. Understanding vulnerability and adaptability to these extremes will also be necessary. For example, vulnerability will vary depending on how organisms experience these temperatures and their ability to access microclimate refugia. However, this species-specific information is limited for many understudied regions of the world, generating a tradeoff between a global, comprehensive assessment and incorporating details of species' biology. We adopt the global approach here, anticipating that unprecedented temperatures will often affect species based on considerations of thermal biology (7). However, these impacts must be validated through observations, given mediating factors like changing phenologies, demographic rates, or microclimatic refugia. Finally, although we focus on terrestrial vertebrates, this approach could easily be expanded to other taxa and ecosystems [cf. (8)].

These exposure analyses can inform international assessments (e.g., IPBES, IPCC) and national action plans for the Global Biodiversity Framework by highlighting recent threats to particular species and regions (*SI Appendix*, Table S1 lists all highly exposed species in 2024 sorted by the ecoregions where they occur). This information can also enable real-time prioritization of recently threatened species and regions for monitoring and mitigation. Exposure estimates could also be applied to forecasted weather to provide an early warning system. Given the immense task of monitoring millions of species globally, we urgently need a scheme to optimize monitoring and mitigation resources to prevent extinctions and ecosystem disruptions.

Methods

To demonstrate the insights and practicality of a rapid climate bioassessment, we examined the thermal exposure of 33,776 terrestrial vertebrates (16, 17). We estimated each species' upper limit of thermal history as the 0.99 quantile of the warmest mean annual temperature recorded at a quarter-degree spatial resolution (~26 km at the equator) across its range, based on ERA5 data from 1940 to 2023 (18). *SI Appendix, Supplemental Methods* describe the rationale for the key modeling decisions: climate variable selection, selecting the spatial and temporal extent and resolution of climate data, species range data, niche limit estimation, and selecting summary statistics.

Data, Materials, and Software Availability. R Code data have been deposited in Github/Zenodo. R code to implement our analysis will be available on Github and Zenodo upon acceptance. Previously published data were used for this work [Climate data are available on Copernicus (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=download), and species range data are available from IUCN (https://www.iucnredlist.org/resources/spatial-data-download) and (17)].

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