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Populations adapt more to temperature in the ocean than on land

A meta-analysis reveals greater variation in heat tolerance within marine than terrestrial taxa. This variation corresponds to the spatial patterns in the maximum temperature populations of marine species experience. Although populations at the equatorward range edges of species' distributions are particularly vulnerable to warming, standing genetic variation within species might promote an adaptive response elsewhere.

The question

Rising temperatures threaten biodiversity. One way to help predict where warming might have the largest effects is to measure how close organisms are to their thermal limits — that is, the maximum temperatures they can withstand. Previous work has examined patterns in thermal limits across species[1,2], but it is also known that variation within species can have an impact[3], with strong effects on the vulnerability to warming. There is increasing attention on the importance of this variation in thermal limits within species[4], and synthesizing the extent of adaptive differentiation of thermal limits within species across taxonomic groups and in different habitats will help generalize these patterns and promote more effective conservation and management decisions. Through a meta-analysis, we measured how much thermal limits vary within species and whether patterns of variation are similar across the marine, intertidal, freshwater and terrestrial realms.

The discovery

We first assembled a dataset of thermal limits from the published literature, drawing from studies that examined latitudinal variation in thermal limits across multiple populations of the same species using controlled laboratory conditions. These experiments minimize confounding effects on patterns in thermal limit variation. Comprising 598 upper-thermal-limit measurements from 305 populations of 61 species, this dataset enabled us to compare patterns in population thermal limits across marine, intertidal, freshwater and terrestrial species. This broad perspective is only possible using a meta-analytic approach, and uncovered general patterns that might not be obvious from the results of an individual study.

Our analysis revealed that there is much more latitudinal variation in the thermal limits within marine and intertidal species compared with species from terrestrial or freshwater habitats (Fig. 1a). This was a surprising finding, as ocean currents have traditionally been expected to homogenize populations by carrying offspring over large distances. We also found that the variation in thermal limits corresponds to differences in the maximum temperature between sites in the marine and intertidal realm, but not in freshwater or terrestrial species (Fig. 1b). In terrestrial taxa, this unexpected lack of a relationship between population thermal limits and maximum environmental temperatures might be linked to an increased capacity for behavioural thermoregulation (that is, the moderation of body temperature through exploitation of fine-scale variation in the thermal landscape, such as using shaded areas to avoid extreme high temperatures) and the exploitation of microclimatic variation (for example, plant species adapted to grow in shaded understory are less likely to be exposed to extreme temperatures than species growing in sunlit canopy gaps), both of which might reduce selection on thermal limits.

The implications

As variation in thermal limits might translate into variation in the vulnerability to warming, our work highlights that a population-level perspective is crucial for accurate predictions about vulnerability to climate change. By accounting for this within-species variation, our results suggest that vulnerability might decrease with increasing latitude within a species' range in the marine and intertidal realms, but not in the terrestrial or freshwater realms. This finding suggests different priorities for conservation and management in marine, intertidal, freshwater and terrestrial habitats. In particular, our results emphasize the importance of maintaining population connectivity in the ocean, which would help standing genetic variation track changing temperatures. Efforts to build climate resilience for terrestrial taxa might focus on maintaining thermal refugia.

Our analysis is limited by the availability of studies that have measured thermal limits in multiple populations of the same species. There is also a strong geographic bias towards the Global North in our dataset that needs to be addressed. To fill key gaps in the data, it is crucial for analogous studies to be conducted in the open ocean, the tropics and polar regions, and, more generally, for financial and logistical support to be available for scientists undertaking this work in the Global South.

The next step is to incorporate this population-level perspective into projections of future species vulnerability. By pairing these data with climate models, we plan to examine how these patterns of within-species variation in thermal limits might affect the responses of species to near-future changes in the climate.

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EXPERT OPINION

"The authors illustrate how species are highly individualized in their response to warming, providing recommendations to move away from taxa-wide generalizations for assessing ecosystem vulnerability under climate change. One strength of this article is its ability to incorporate studies that document similar phenomena but use different descriptive language, which usually makes comparisons difficult at face value." **Richelle Tanner, Chapman University, Orange, CA, USA.**

FIGURE

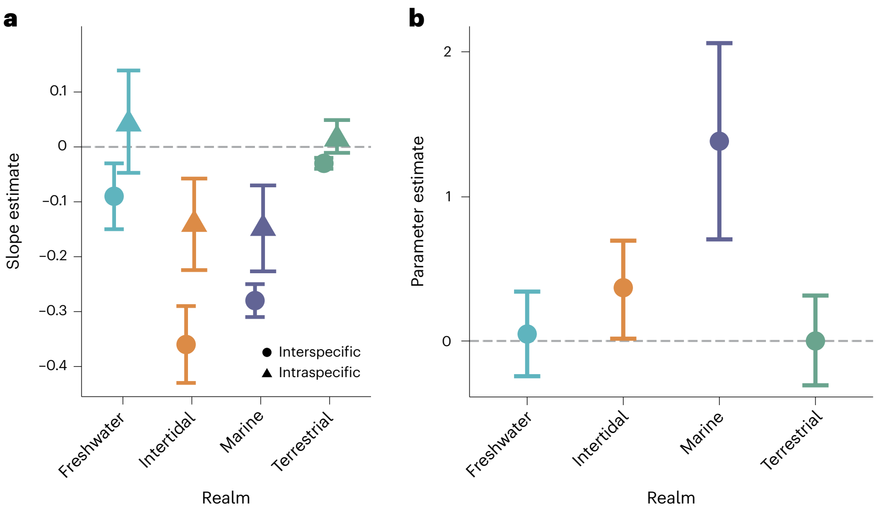

Fig. 1 | Within-species variation in thermal limits. a, Thermal limit slopes (change in thermal limit per degree latitude; ± standard error) indicate more variation in the ocean than on land. Although substantial, there tends to be less variation within (triangular symbols) than across species (circular symbols). **b**, Meta-regression model parameter estimates (±95% confidence interval) show that thermal limit variation across populations corresponds to differences in maximum temperature between sites for marine and intertidal species, but not freshwater or terrestrial species. © 2022, Sasaki, M. et al.

BEHIND THE PAPER

This project would not have been possible without the Research Coordination Network for Evolution in Changing Seas, supported by the US National Science Foundation. This network aimed to synthesize and advance topics at the intersection of marine science and evolutionary biology. Our project was one of several that originated from a dedicated Synthesis Workshop at Shoals Marine Laboratory in the summer of 2019. In a textbook example of serendipity, our group comprised individuals possessing a wide range of backgrounds and expertise (including experts in marine and terrestrial realms, plant and animal species, and empirical and meta-analytic studies), but a shared interest in how local adaptation might affect responses to climate change. We are grateful to have shared this experience, and hope it will encourage others to undertake similar collaborations in the future. **M.C.S.**

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FROM THE EDITOR

"There is an increasing realization that in order to understand how species will respond to climate change, looking at those species as a single unit might not be the best approach. Here, the authors investigate within-species differences in thermal tolerance. What stands out is this focus and the scope of the work, which covers a large range of species from terrestrial, marine and freshwater environments." **Editorial Team, *Nature Climate Change*.**