

Meta-analysis reveals less sensitivity of non-native animals than natives to extreme weather worldwide

Received: 16 March 2023

Accepted: 21 September 2023

Published online: 6 November 2023

 Check for updates


Shimin Gu ^{1,4}, Tianyi Qi ^{1,2,4}, Jason R. Rohr ³ & Xuan Liu ^{1,2} 

Extreme weather events (EWEs; for example, heatwaves, cold spells, storms, floods and droughts) and non-native species invasions are two major threats to global biodiversity and are increasing in both frequency and consequences. Here we synthesize 443 studies and apply multilevel mixed-effects metaregression analyses to compare the responses of 187 non-native and 1,852 native animal species across terrestrial, freshwater and marine ecosystems to different types of EWE. Our results show that marine animals, regardless of whether they are non-native or native, are overall insensitive to EWEs, except for negative effects of heatwaves on native mollusks, corals and anemone. By contrast, terrestrial and freshwater non-native animals are only adversely affected by heatwaves and storms, respectively, whereas native animals negatively respond to heatwaves, cold spells and droughts in terrestrial ecosystems and are vulnerable to most EWEs except cold spells in freshwater ecosystems. On average, non-native animals displayed low abundance in terrestrial ecosystems, and decreased body condition and life history traits in freshwater ecosystems, whereas native animals displayed declines in body condition, life history traits, abundance, distribution and recovery in terrestrial ecosystems, and community structure in freshwater ecosystems. By identifying areas with high overlap between EWEs and EWE-tolerant non-native species, we also provide locations where native biodiversity might be adversely affected by their joint effects and where EWEs might facilitate the establishment and/or spread of non-native species under continuing global change.

Climate change and invasive species are two major threats to global biodiversity^{1,2}. Understanding how climate change influences invasions of non-native species is crucial for mitigating their joint impacts in the context of accelerating global change³. In addition to gradual shifts in temperature and precipitation, scientists have recognized that the increasing frequency and magnitude of extreme weather events (EWEs), such as heatwaves, cold spells, storms, floods and droughts⁴,

can result in even greater biological consequences than changes to climate means⁵. Comparison of the responses of native and non-native species to EWEs is crucial for developing early and effective strategies for native species conservation and non-native species prevention under accelerating EWEs associated with climate change⁶.

Considerable evidence from native species has shown that EWEs can cause declines in population abundances and species richness,

¹Key Laboratory of Animal Ecology and Conservation Biology, Institute of Zoology, Chinese Academy of Sciences, Beijing, China. ²University of Chinese Academy of Sciences, Beijing, China. ³Department of Biological Sciences, Environmental Change Initiative, University of Notre Dame, Notre Dame, IN, USA. ⁴These authors contributed equally: Shimin Gu, Tianyi Qi.  e-mail: liuxuan@ioz.ac.cn

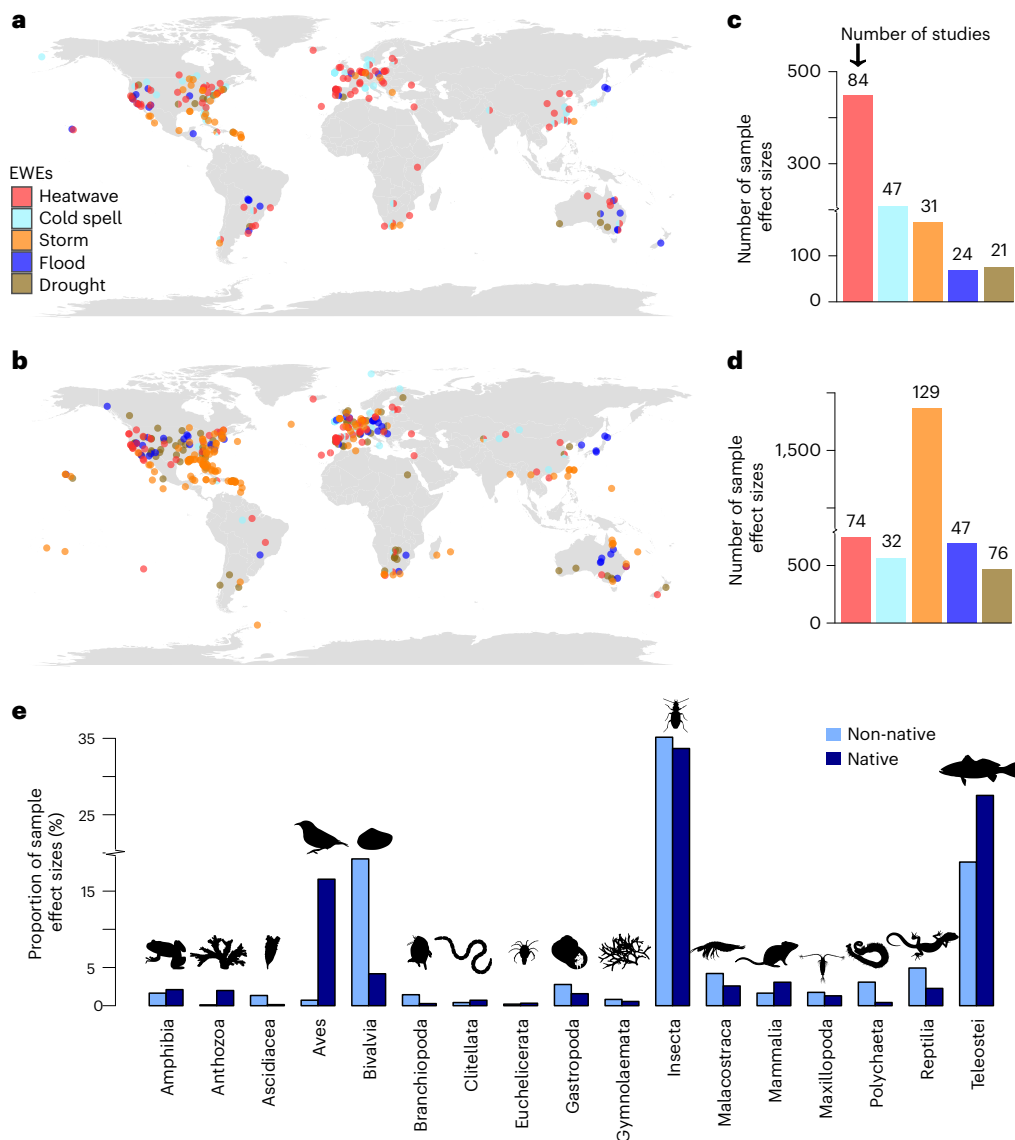


Fig. 1 | Distribution of non-native and native species under EWEs from 443 studies. a–e. Point colours indicate different types of EWE in 235 locations for non-native species (a) and 394 locations for native species (b). The bar chart

shows the number of effect sizes for different EWE groups of non-native (c) and native species (d), and the proportions of sample effect sizes across taxa (e). Animal silhouettes in e were obtained from PhyloPic (www.phylopic.org).

restructure community composition and limit post-event recovery across ecosystems^{7–13}. However, published studies also found that non-native arthropods, mammals, shellfishes and fishes might be relatively tolerant of, or even respond positively to EWEs^{14–17}. There are several possible mechanisms to explain different responses of non-native and native species to EWEs¹⁸. First, EWEs often result in considerable mortality of native species and could thus create more vacant niches to facilitate non-native species invasions^{19,20}. For example, severe drought events decreased native invertebrates and fishes by increasing water salinity, facilitating the establishment of non-native salt-tolerant counterparts^{14,15}. Second, invaders can have more rapid growth rates, stronger competitive abilities, higher phenotypic plasticity, broader tolerance of disturbance and quicker recovery and proliferation than natives^{21–24}. For example, the abundance of most native fish in the Rio Minho estuary, Portugal, declined but abundance of non-native fish increased after extreme droughts and floods, and thus the fish assemblage there was dominated by a few invasive fish species after extreme weather events²⁵. Non-native mesozooplankton species exhibit higher flexibility to marine heatwaves than native species in the

Sevastopol Bay²⁶. Non-native species showed less susceptibility and recovered more quickly than native species in the marine epibenthic fouling community of Bodega Harbor, California, USA²⁷. Despite these striking case studies, a thorough understanding of the general effect of EWE and multiple taxonomic groups is still lacking, impeding forecasts of the responses of non-native species to climate change and their joint impacts on native species. It is critical to fill this literature gap because resources for managing and mitigating biological invasions and climate change are limited. Thus, it is crucial to identify the most affected regions and problematic taxa so that those resources are targeted properly.

Here we applied a multilevel mixed-effects meta-regression to conduct a global synthesis of non-native and native animal responses to EWEs (Supplementary Fig. 1). These species spanned terrestrial, freshwater (mammals, birds, amphibians, reptiles, fish and invertebrates) and marine ecosystems (surface and benthic fishes and benthic invertebrates). Each measured effect size was assigned to one of eight major response categories: physiology, body condition, behaviour,

life history traits, abundance, distribution, community structure and recovery after EWEs. Our analyses covered five main types of EWEs: heatwaves, cold spells, storms, floods and droughts. Furthermore, on the basis of the results of our meta-analyses, we quantified the spatial overlap between the distributions of EWE-tolerant non-native species and the EWE hotspots. These overlap analyses should identify locations where native biodiversity might be adversely affected by the joint effects of non-native species and EWEs, and where EWEs might facilitate the future establishment and/or spread of non-native species.

Results

Overall EWE distributions

Across the globe, there were a total of 973 measured effect sizes from 177 peer-reviewed studies across 187 non-native species and 4,330 measured effect sizes from 335 peer-reviewed studies across 1,852 native species (Supplementary Fig. 1). These reported studies on the effects of EWEs on animals were mainly distributed in North America and Europe, and sporadically distributed in South America, southern Africa, East Asia and southeast Australia (Fig. 1a,b). Eighty four percent of studies on non-native species (149/177) and 95% of studies on native species (317/335) focused on responses to only one type of EWE (Fig. 1c,d and Supplementary Data 1). Overall, our analyses included effect sizes of EWEs on non-native animals and native animals spanning 6, 7 and 10 classes of terrestrial, freshwater and marine organisms, respectively (Fig. 1e) and three orders of magnitude in body size (for example, smallest mean body size, Insecta: 0.81 ± 0.22 mm; largest Mammalia: $1,531.33 \pm 211.00$ mm).

Species can differ in their exposure to EWEs that may influence selection for EWE tolerance. We assessed exposure differences by comparing the average magnitude of the EWEs within the geographic ranges of each native and non-native species in our database. We found limited evidence that non-native and native species experience significantly different magnitudes of EWE exposures (Supplementary Fig. 2). We also found little evidence in our samples that ecosystem types differed significantly in their magnitudes of EWEs (Supplementary Fig. 2), except that oceans have more days of heatwaves and cold spells than terrestrial and freshwater ecosystems (Supplementary Fig. 2).

Responses of non-native and native animals to EWEs

Overall, we found that non-native species had 24.8% positive, 31.8% negative and 43.4% neutral responses (confidence intervals (CIs) crossing zero) to EWEs. Native species had 12.7% positive, 20.5% negative and 66.8% neutral responses to EWEs. Both non-native and native species exhibited positive, negative and neutral responses to each type of EWE (Fig. 2). Further multilevel mixed-effects metaregression models showed that non-native species only responded negatively to heatwaves in terrestrial ecosystems, whereas native species were adversely affected by heatwaves, cold spells and droughts (Fig. 3a). In freshwater ecosystems, non-native species only responded negatively to storms, but native species responded negatively to heatwaves, storms, floods and droughts. We even observed positive effects of heatwaves and cold spells on freshwater non-native species (Fig. 3b). Marine animal species overall were insensitive to EWEs, regardless of whether they were non-native or native (Fig. 3c). Egger's test indicated limited evidence for publication bias associated with the overall responses of non-native and native animals to EWEs (Supplementary Table 1). In addition, the omnibus Wald-type test showed a good fit of the model to the data (Supplementary Table 4). Hence, the greater tolerance of non-native animals than natives to EWEs does not appear to be artefactual.

To assess whether the responses of non-native and native species were dependent on certain taxa or biogeographic realms (Nearctic, Neotropic, Palaearctic, Indomalayan, Afrotropic and Australasian in terrestrial and freshwater ecosystems; Agulhas, Cold Temperate

Northeast Pacific, Lusitanian, Northern European Seas, Tropical North-western Atlantic, Warm Temperate Northeast Pacific and Warm Temperate Northwest Atlantic in marine ecosystems), we reconducted the analyses above including taxonomic group and realm as independent variables interacting with non-native/native status (Supplementary Figs. 3 and 4). Analyses across taxonomic groups (Supplementary Fig. 3) and biogeographic realms (Supplementary Fig. 4) produced similar results as the overall analyses. One insight revealed from this separate analysis was that the negative response of terrestrial non-native animals to heatwaves was only a product of the sensitivity of non-native insects (mean effect size: -1.188 , $P < 0.001$, Supplementary Fig. 3).

Among response variables, in terrestrial ecosystems, EWEs only had negative effects on abundance of non-native species, but adversely affected body condition, life history traits, abundance, distribution and post-event recovery of native species (Fig. 4a). In freshwater ecosystems, EWEs had negative effects on body condition and life history traits of non-native species, and on community structure of native species (Fig. 4b). Across terrestrial and freshwater ecosystems, we did not observe negative effects of EWEs on the distribution, abundance (except terrestrial insects: mean effect size -0.844 , $P = 0.004$), community structure or recovery of non-native animals (Fig. 4a,b), which thus appear to maintain population stability and community structure during and after EWEs. We even observed a positive response of non-native species' physiology, behaviour and recovery to EWEs in terrestrial and freshwater ecosystems (Fig. 4a,b). In marine ecosystems, non-native species presented overall positive responses to EWEs except for body condition and life history traits (Fig. 4c).

Overlap between non-native species and EWEs

We further conducted spatial overlap analyses between EWE hotspots and suitable habitat for non-native animals to identify where native species might be particularly vulnerable to the combined effects of EWEs and non-native species. To do so, we first applied species distribution modelling to predict those grids with suitable areas for establishment of non-native animals and overlaid these grids with maps of EWE hotspots (see more details in Supplementary Methods). We then calculated the net effect of each non-native animal to EWEs in each overlapped grid as the proportions of positive plus neutral responses minus negative response on the basis of the sample effect sizes in the meta-analyses. The accumulative net effect for each grid was obtained to reflect the overall tolerance of all potential non-native species to EWEs.

Our analyses show that overlapping areas of highly EWE-tolerant non-native species and EWEs hotspots are generally distributed in mid-to-high latitudes, but these patterns did depend on EWE type. For heatwaves, overlapping areas were mainly distributed in mid-latitude regions, including west and east-southern United States, southern Brazil, southern Mediterranean, South Africa, east-southern Asia, south Australia, New Zealand, west-northern coast and islands in the Indian Ocean, and west coast and islands in the Pacific Ocean (Fig. 5a). For cold spells, overlapping areas were mainly distributed in high-latitude regions, including northern areas of the United States and Canada, southern Argentina, northern Europe, western coastal regions of Australia, east coast of the North Atlantic Ocean, south coast of the Baltic Sea and east coast of the Arctic Ocean (Fig. 5b). For storms, overlapping areas were sporadically distributed from low to high latitudes, including Latin America, India, high-latitude European countries (that is, the United Kingdom and Norway), south-western and north-eastern Australia, Northern Atlantic Ocean and the west coast of the Pacific Ocean (Fig. 5c). For floods and droughts, overlapping areas were distributed in mid latitudes of the Mediterranean region, mid-Asia, southern Australia, and East and Southeast Asia. In South America, overlap was associated with floods in western Amazon and southern Brazil but with droughts in northern Amazon and southern Argentina. In Africa, overlap coincided with floods in the middle of Africa but with droughts in northern Africa (Fig. 5d,e).

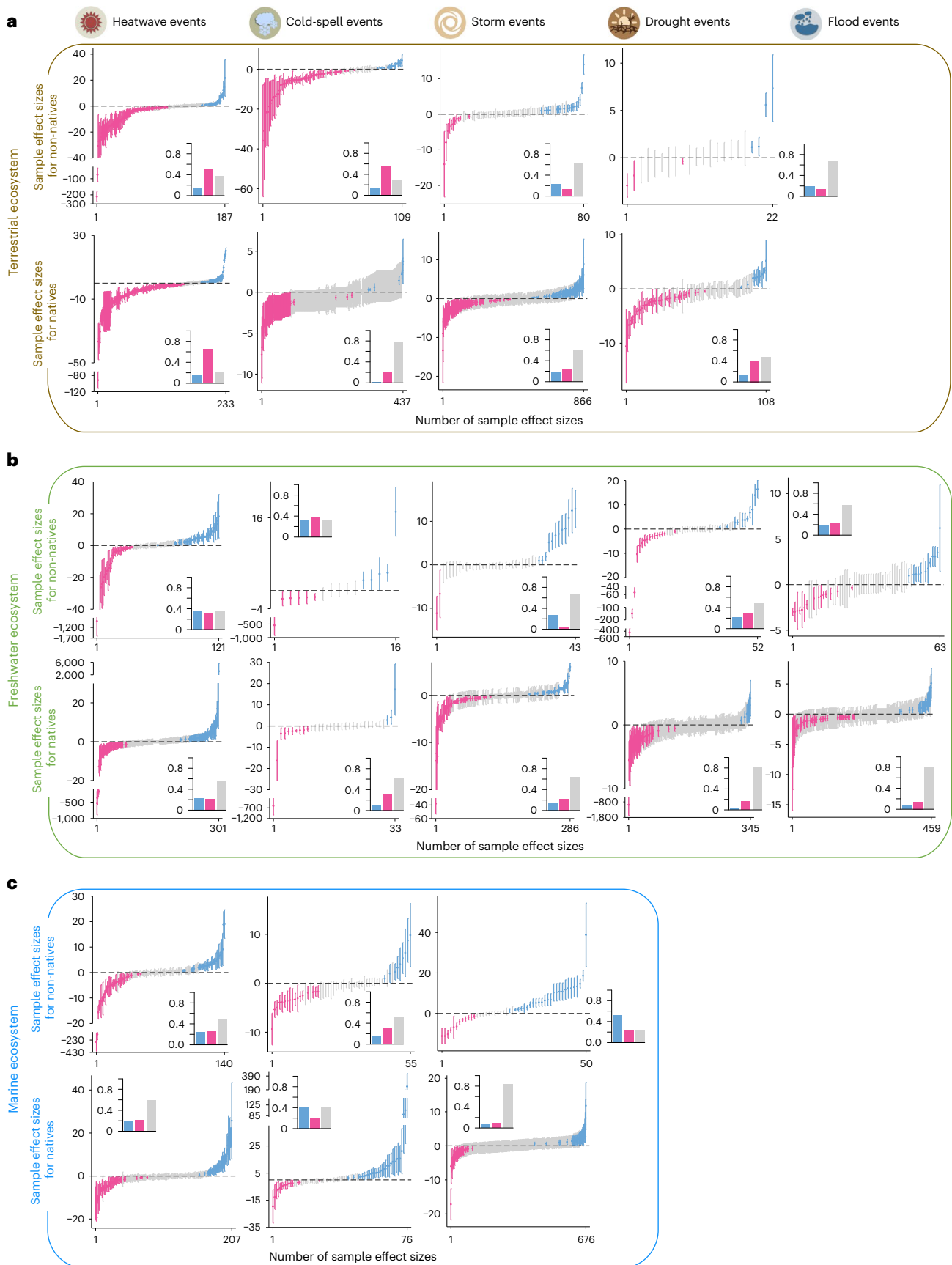


Fig. 2 | Sample effect sizes of non-native and native species in responding to EWEs. a–c, Sample effect sizes in terrestrial (a), freshwater (b) and marine (c) ecosystems. The horizontal dashed lines represent the position where the sample

effect size is zero. The heights of barplots are relative proportions of positive (blue), negative (pink) and neutral (grey) (CIs crossing zero) effect sizes, and were standardized, ranging from 0 to 1.

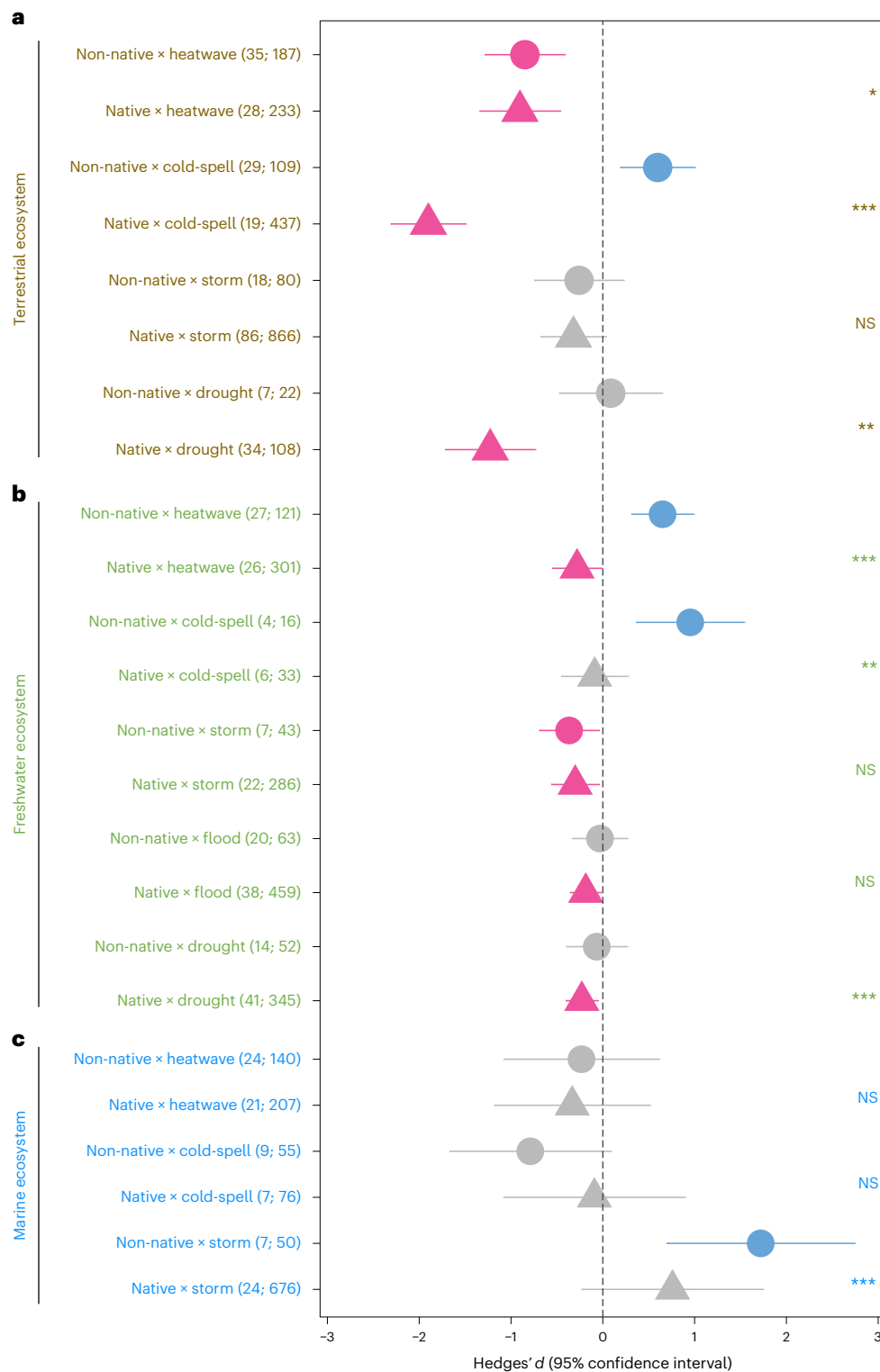


Fig. 3 | A comparison of non-native (circle) and native species (triangle) responses to five different types of EWE. a–c, Effect sizes (Hedges' *d*) for non-native and native species' responses to heatwave, cold-spell, storm, flood and drought events in terrestrial (a), freshwater (b) and marine (c) environments, estimated from metafor. Error bars are 95% CIs. A Wald-type test was used to detect whether a mean effect size estimate was significant when the 95% CI did not encompass zero. In a, *P* values of non-native species responses to EWEs were: heatwave (0.0001), cold spell (0.004), storm (0.298) and drought (0.763); *P* values of native species responses to EWEs were: heatwave (<0.0001), cold spell (<0.0001), storm (0.079) and drought (<0.0001). In b, *P* values of non-native species responses to EWEs were: heatwave (0.0002), cold spell (0.002), storm (0.027), flood (0.842) and drought (0.698); *P* values of native species

responses to EWEs were: heatwave (0.042), cold spell (0.635), storm (0.023), flood (0.032) and drought (0.011). In c, *P* values of non-native species responses to EWEs were: heatwave (0.592), cold spell (0.079) and storm (0.001); *P* values of native species responses to EWEs were: heatwave (0.442), cold spell (0.856) and storm (0.132). Numbers in parentheses represent the number of studies and measured effect sizes, respectively. Blue, significantly positive mean effect sizes; pink, significantly negative mean effect sizes; grey, non-significant mean effect sizes. The asterisks and 'NS' indicate significant and non-significant differences, respectively, between non-native and native species to the particular EWE; **P* < 0.05, ***P* < 0.01, ****P* < 0.001, performed using an omnibus test (Supplementary Table 2). Multiple comparisons were not performed in data analyses. The two-sided *P* value was used to judge significance.

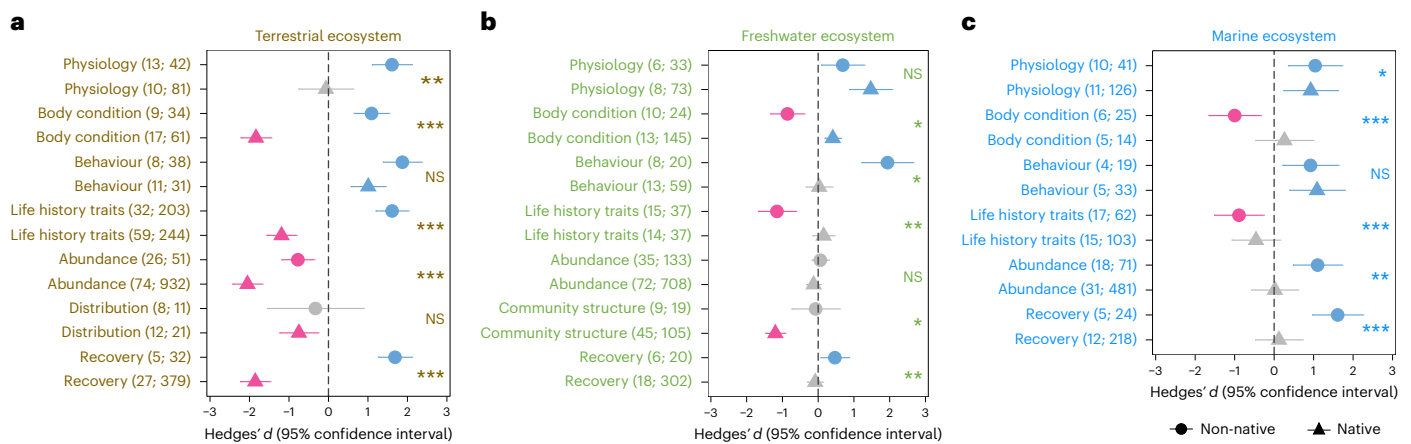


Fig. 4 | A comparison of non-native (circle) and native (triangle) species responses to EWEs for eight response variables. a–c, Effect sizes (Hedges' d) for the non-native and native species responding to EWEs in terrestrial (a), freshwater (b) and marine (c) ecosystems, estimated from metafor. Error bars are 95% CIs. A Wald-type test was used to detect whether a mean effect size estimate was significant when the 95% CI did not encompass zero. In a, P values of non-native species response variables to EWEs were: physiology (<0.0001), body condition (<0.0001), behaviour (<0.0001), life history traits (<0.0001), abundance (0.0003), distribution (0.597) and recovery (<0.0001); P values of native species response variables to EWEs were: physiology (0.854), body condition (<0.0001), behaviour (<0.0001), life history traits (<0.0001), abundance (<0.0001), distribution (0.003) and recovery (<0.0001). In b, P values of non-native species response variables to EWEs were: physiology (0.026), body condition (0.0004), behaviour (<0.0001), life history traits (<0.0001), abundance (0.630), community structure (0.839) and recovery (0.021); P values of native species response variables to EWEs were: physiology (<0.0001), body

condition (0.0004), behaviour (0.882), life history traits (0.337), abundance (0.224), community structure (<0.0001) and recovery (0.463). In c, P values of non-native species response variables to EWEs were: physiology (0.003), body condition (0.003), behaviour (0.011), life history traits (0.005), abundance (0.0005) and recovery (<0.0001); P values of native species response variables to EWEs were: physiology (0.009), body condition (0.487), behaviour (0.003), life history traits (0.143), abundance (0.950) and recovery (0.690). Numbers in parentheses represent the number of studies and measured effect sizes, respectively. Blue, significantly positive mean effect sizes; pink, significantly negative mean effect sizes; grey, non-significant mean effect sizes. The asterisks and 'NS' indicate significant and non-significant differences, respectively, between non-native and native species in their responses to EWEs; * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, performed using an omnibus test (Supplementary Table 3). Multiple comparisons were not performed in data analyses. The two-sided P value was used to judge significance.

Our results were robust to different criteria used to define overlap hot-spots (Supplementary Fig. 5, see details in Supplementary Methods).

Discussion

The present study provided a comparative evaluation of the responses of non-native and native animals to historical EWEs across taxa and ecosystems at the global scale. Although there were both 'winners' and 'losers' across both non-native and native species and ecosystems (Fig. 2), proportionally there were more positive responses of non-native than native animals to EWEs, making the mean response to EWEs less negative for non-native than for native species. Our further meta-analyses that controlled for spatial and taxonomic pseudoreplication generally showed that non-native species are less sensitive to most EWEs than their native counterparts, especially in terrestrial and freshwater ecosystems. This high tolerance of non-native species to EWEs compared with native species particularly represented a strong capacity of non-native species to maintain population stability after EWEs across ecosystems. We found limited evidence of publication bias associated with the overall responses of non-native and native animals to EWEs. However, there was detectable publication bias for non-native animal responses to terrestrial cold spells, and for native animal responses to terrestrial heatwaves and cold spells, and freshwater floods and droughts (Supplementary Table 1), which is a common phenomenon in meta-analyses when disciplines are partial to studying certain effects²⁸.

There are several possible explanations for why non-native animals tend to be less sensitive to most EWEs than native species within the same taxonomic class. First, many non-native species exhibit rapid growth rates, long spawning seasons, short longevities, high competitive abilities, rapid population recolonization and trophic preference for detritus that could help them take advantage of limited resources and maintain population sizes during and after EWEs^{18,29,30}. Non-native

species also often have higher plasticity than native species^{18,31,32}. For example, the abundance of the invasive South American tomato pinworm was tolerant of acute and chronic temperature stress because of high thermal plasticity in invaded ranges³³. As another example, an invasive prawn showed higher plasticity of upper thermal limits than native prawns and was thus less vulnerable to extreme thermal events³⁴. Finally, the high propagule pressure and meta-population structure (that is, connectivity) of many non-native species³⁵ often make their populations more resilient to the adverse effects of EWEs than native species^{18,36}. Indeed, population-level response variables of non-native species, such as their abundance, distribution and recovery, were generally insensitive to EWEs (Fig. 4). Nevertheless, we also observed some negative responses of terrestrial non-native animals to heatwaves, particularly for Insecta (Fig. 3 and Supplementary Fig. 3). Additional analyses further showed that heatwaves could negatively impact insect body size, development time, growth rate, longevity, reproduction and survival rate (Supplementary Table 5). These findings support a previous insect study revealing that life history plasticity was weak in insect responses to extreme temperatures³⁷.

Freshwater non-native animals responded positively to heatwaves and cold spells, consistent with some previous studies on freshwater crustaceans³⁸ and mussels^{39,40}. Given that 90.8% (109/120) of non-native freshwater animals in heatwave studies are warm-adapted and cold-adapted fishes and invertebrates (including Bivalvia, Gastropoda and Malacostraca) introduced through aquaculture (Supplementary Data 1)⁴¹, one potential explanation for the positive response of freshwater non-native animals to heatwaves and cold spells is ecological memory theory⁴². This theory predicts that adaptations to environmental change are positively related to the past disturbance events experienced by a species^{43,44}. Future studies should test whether native species exposed to more severe historical EWEs are indeed more tolerant of EWEs.

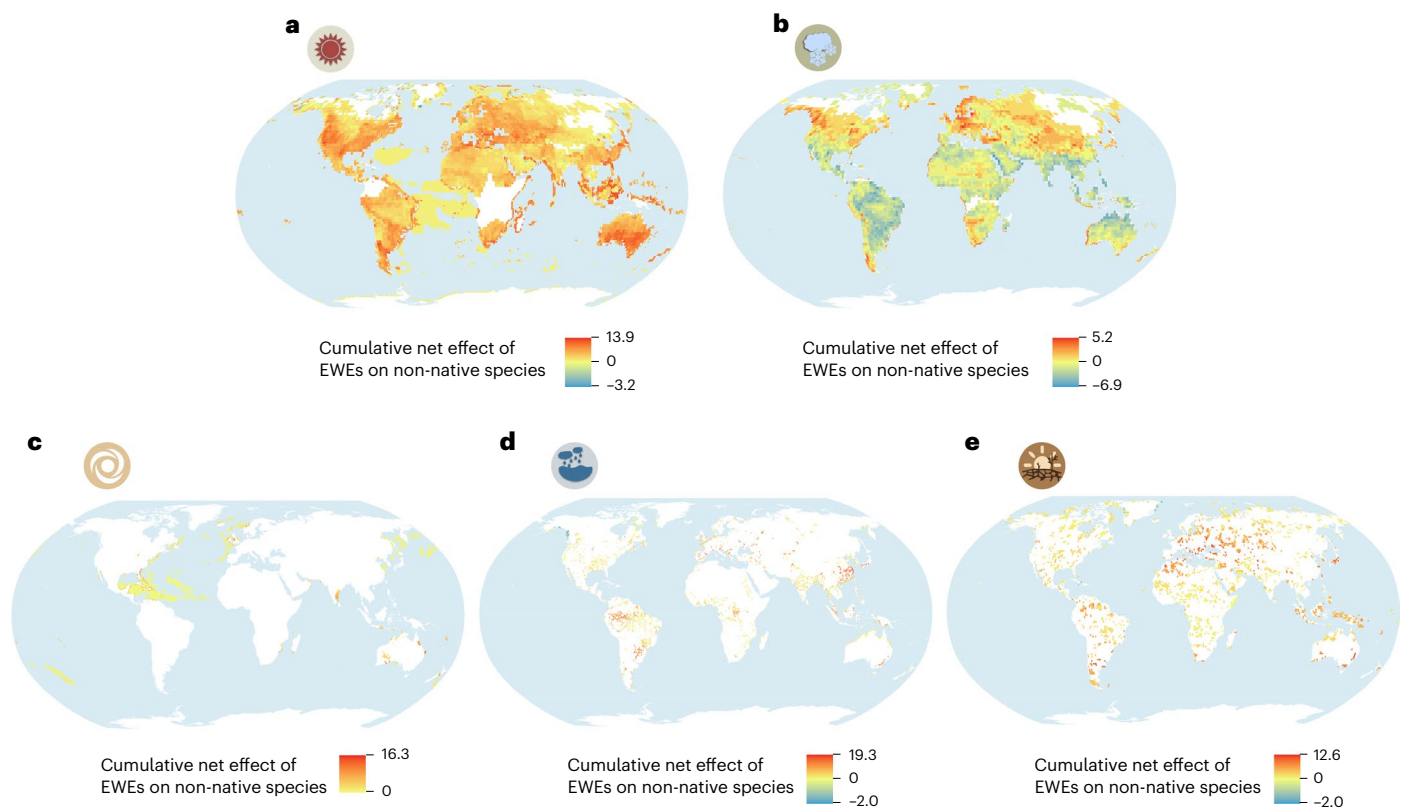


Fig. 5 | Overlapping areas between potential distributions of non-native species that are tolerant of EWEs and EWE hotspots worldwide. a–e. Global maps showing the accumulative net effects of predicted non-native animals in areas with the top 20% occurrences of heatwaves (a), cold spells (b), storms (c), 100-yr floods (d) and extreme droughts (SPI \leq -1.5) (e) at 5-arcmin resolution. Higher values indicate greater combined risks of invasions and EWEs, and negative values mean that there are more negative responses of non-native species to EWEs than positive and neutral responses in those areas. The ‘white’ colour in the maps indicates land areas without overlaps between predicted distributions of non-native species and EWEs. Taxonomic information for animals in each corresponding EWE type used in the overlap analyses: for heatwaves, terrestrial (Amphibia, Aves, Euchelicerata and Insecta), freshwater

(Bivalvia, Branchiopoda, Gastropoda, Malacostraca and Teleostei) and marine (Ascidiacea, Bivalvia, Gastropoda, Gymnolaemata, Malacostraca, Maxillopoda, Polychaeta and Teleostei) species were included; for cold spells, terrestrial (Amphibia, Insecta, Mammalia and Reptilia), freshwater (Gastropoda and Teleostei) and marine (Bivalvia, Malacostraca, Maxillopoda and Polychaeta) species were included; for storms, terrestrial (Amphibia, Aves, Insecta, Mammalia and Reptilia), freshwater (Bivalvia, Clitellata, Gastropoda and Teleostei) and marine (Malacostraca and Teleostei) species were included; for floods, terrestrial (Amphibia and Aves) and freshwater (Bivalvia, Insecta, Malacostraca and Teleostei) species were included; for droughts, terrestrial (Insecta) and freshwater (Bivalvia, Gastropoda, Malacostraca and Teleostei) species were included.

Interestingly, in contrast to terrestrial and freshwater species, both non-native and native marine species were insensitive to EWEs. Importantly, this finding was not a product of the lower magnitude of EWEs in marine than in terrestrial and freshwater environments, as we observed few differences in the magnitude of EWEs among ecosystem types within the geographic ranges of each native and non-native species in our meta-analysis (Supplementary Fig. 2). The only difference we did observe suggested that oceans had significantly more days experiencing heatwaves and cold spells than terrestrial and freshwater ecosystems (Supplementary Fig. 2). The tolerance of non-native marine species to EWEs supports previous findings that marine invaders were generally insensitive to ocean heatwaves^{26,27}, cold spells^{45,46} and storms^{16,47}. For instance, non-native bryozoans and crustaceans maintained their community composition and population abundance, respectively, in response to marine heatwaves^{26,27}. In contrast, it has been reported extensively that marine heatwaves are pervasive stressors to native ocean species, especially anemones and corals (Anthozoa)^{7,48}. Indeed, we observed a negative response of native Anthozoa to marine heatwaves (mean effect size -1.632, $P < 0.001$), consistent with past studies^{7,48}. In addition, our results support a recent review on the negative response of benthic invertebrates (that is, Bivalvia) to marine heatwaves (mean effect size -0.869, $P = 0.028$), which was possibly due to their limited abilities

to disperse to more suitable habitats⁷. Regarding the insensitivity of marine native and non-native species to cold spells, Maxillopoda and Polychaeta dominated the effect sizes for this test and the literature reports that these taxa tend to be cold-adapted species and thus have high performance at low temperatures^{45,46}. Finally, we found that marine non-native and native species were also insensitive to storm events. Teleostei and Bivalvia dominated the effect sizes for this test. Our finding is consistent with previous studies that showed that fishes and Bivalvia were insensitive to storms, possibly because they are either mobile enough⁴⁹ or use ocean currents⁵⁰ to seek refuge during storms, respectively.

Our global analysis of spatial overlap between non-native species and EWE hotspots identified several vulnerable areas in mid-to-high latitudes including North America, Europe, Oceania, temperate Asia inland, East and Southeast Asia, South America and Africa and marine regions in low-to-mid latitude areas of the Atlantic Ocean, west-northern coast of the Indian Ocean, south coast of the Baltic Sea, east coast of the Arctic Ocean and west coast of the Pacific Ocean where native species might face joint impacts of invasive species and EWEs. Although the invasion hotspots we identified were only based on habitat suitability for establishment, we found that these predicted hotspots have also been reported as areas with frequent non-native species introductions^{35,51}, which imply a potentially high overall invasion

risk in these regions. Furthermore, our identified EWE epicentres have also been validated by several predictive models^{52–55}.

Our present study also provided some useful directions for future studies. First, this study focused on the direct effect of EWEs to native and non-native species, but EWEs can also have indirect impacts on biota. For example, prolonged heatwaves can promote lethal hypoxic/anoxic conditions⁵⁶. EWEs can cause severe population declines by damaging habitat-forming species, such as corals, forests, mangroves and mussel⁷, or by removing key prey species from food webs⁵⁷. Furthermore, for marine species, the effects of EWEs might be more severe in intertidal and shallow subtidal zones than in deeper/offshore marine waters owing to increased exposure to EWEs. Indeed, we found that non-native species in deeper water (species recorded maximum depth >200 m) exhibited positive responses to EWEs (mean effect size 2.262, $P = 0.009$). However, we did not detect the negative effect of EWEs on either non-native or native species in intertidal and shallow subtidal zones. As we only have 41 samples (3.3% of all marine species samples) for deeper/offshore species, a larger sample size would be useful to more rigorously compare the responses of nearshore vs offshore species. Finally, the invasion and EWE overlap areas in the present study were based on non-native animal tolerance to EWEs. We acknowledge that some EWE-sensitive non-native species might still have the potential to exert ecological forces on existing ecosystems. However, under the limited resources that can be used to manage biological invasions and climate change, we suggest that future studies should prioritize these less-sensitive animals in locations of overlap so that timely mitigation strategies can be implemented if native species exhibit declines associated with biological invasions and intensified EWEs driven by global change. Our present analyses could facilitate early prevention schemes against biological invasions and climate change globally and improve the development of sustainable policies in the era of global change.

Methods

Literature search

We conducted a systematic literature search on ISI Web of Science (all databases) and Scopus to collect published papers from the year 1864 to 24 April 2023. The following search terms were entered into the 'Topic' field in ISI Web of Science and in 'All fields' for Scopus: ('storm' OR 'hurricane' OR 'cyclone' OR 'typhoon' OR 'tornado' OR 'wildfire' OR 'extreme snow' OR 'extreme ice' OR 'extreme heat' OR 'heat wave' OR 'extreme high temperature' OR 'extreme cold' OR 'cold wave' OR 'extreme' OR 'extreme drought' OR 'extreme rainfall' OR 'extreme precipitation' OR 'flood') AND ('abundance' OR 'behaviour' OR 'richness' OR 'reproduction' OR 'mating' OR '*diversity' OR 'composition' OR 'predation' OR 'parasit' OR 'herbivory' OR 'activity' OR 'timing' OR 'physiology' OR 'development' OR 'trophic' OR 'biomass' OR 'survival' OR 'growth') AND ('species' OR 'population' OR 'ecological community' OR 'ecosystem*'). This resulted in a total of 147,212 unique studies that were screened for inclusion in our meta-analysis. We also combined studies from four previous meta-analyses of the animals' responses to EWEs^{8,13,58,59} (Supplementary Fig. 1).

Screening process and data exclusion criteria

First, we screened the title, key words and abstract to determine candidate studies that focused on effects of EWEs on non-native or native species. Review papers and those without quantitative analyses were excluded. We excluded studies on the basis of the following criteria: (1) no statistical comparisons of EWE effects to controls, insufficient information on sample size, mean or variance, or no reporting of the animal species; (2) only lab work simulating the EWE-associated changes in salinity but no direct test of the EWE effects on aquatic or saltmarsh living organisms; (3) intra- or interspecific interactions under changed microclimatic or soil habitats induced by EWEs; (4) sea-level or manipulated water-level rise that resulted in further submergence

or inundation; (5) human burning practices in managed grassland or forests; and (6) comparison of differences in litter or carrion of species along a gradient of EWEs. We excluded these studies because there were either no measured response variables of species to EWEs (2 to 5), or the reported measured variables were only based on the species' litter or carrion but not the living organisms (6). We then divided the studies^{14–16,25–27,38,39,45–47,50,60–490} that passed this screening into those on non-native and native species.

Data extraction and measurable categories of response variables

We extracted sample size, mean and variance values in the control (that is, those samples that did not experience EWEs) and treatment groups (that is, those samples that experienced EWEs) from each study. Particularly, for studies based on successive or long-term observational data, the value at the closest time before EWEs was the control, and the averaged value around the time of EWE was the treatment⁴⁹¹. We only extracted the most extreme EWE level from manipulative experiments testing more than two EWE levels. GetData graph Digitizer (v.2.24) was used to extract values from figures in the studies. We extracted median and interquartile range in boxplots to quantify the mean and deviation values when studies reported statistical results of parametric tests or when the data had been transformed to meet normality in the literature⁴⁹². From each study, we also recorded species name, taxon, ecosystem, type of EWE, coordinates of study/sampling sites and reference information.

We categorized response variables into eight categories. At the population level, categories included life history traits (that is, survival rate, reproduction, longevity, development time, growth rate), abundance (that is, population density or size, capture or encounter rate, number count and relative abundance), distribution (that is, occupancy, home range, spatial distribution, foraging zone, territory size), biodiversity (that is, number of species, richness index, population genetic structure) and recovery (that is, recovery of population abundance and/or community composition after EWEs). At the individual level, categories included physiology (that is, gene expression, immune responses, protein and hormone-related chemical compounds, respiration and critical thermal limits), body condition (that is, body mass and size) and behaviour (that is, activity, dietary, feeding or foraging amount, inter-/intraspecific competition, migration or movement and habitat selection) (Supplementary Table 6). These eight groups were only included in our main analyses if they contained at least 10 effect sizes from multiple studies for each class or biogeographic realm⁴⁹³. The response variables were standardized before the analyses to ensure that all reported responses were in the same direction; that is, larger was always better and smaller worse for each response variable.

Meta-analysis

We used a standardized mean difference with heteroscedastic population variances (SMDH) in the two groups, which is a widely used and robust method to calculate effect sizes⁴⁹⁴. Hedges' d effect sizes were obtained after correcting for sample bias in SMDH using the 'escalc' function in the 'metafor' (v.3.0-2) package⁴⁹⁵. To evaluate responses of mean effect sizes to moderator variables, we ran multi-level mixed-effects meta-regression models using the 'rma.mv' function in the 'metafor' (v.3.0-2) package, which allowed us to account for the nested structure and non-independence of observations from a single study. To control for non-independence among variables within a study, we adopted the method used in ref. 28 and set paper ID (a set of numbers used to distinguish different studies) as a random intercept. In addition, we included different taxonomic levels (Class, Order and Family) as a random effect to control for phylogenetic covariance in EWE tolerances among species. We used Family in our main analysis because of its lower Akaike information criterion value than models using Class or Order as random intercept (Supplementary Table 7).

We also included response variable category as a random effect to control for the pseudoreplication issue of different samples among categories of variables. We included interaction between non-native/native status and the occurrence of a given EWE as a fixed effect to test for differences in responses of native and non-native species to EWEs. We considered the mean effect size estimate to be significant when the 95% confidence interval (CI) did not encompass zero. The approximate residual heterogeneity of models was assessed using Cochran's Q (Q_E), and the omnibus Wald-type test (Q_M) was used to assess model performance in explaining the heterogeneity attributed to a given moderator variable⁴⁹⁶. We ran Egger's regression test for publication bias⁴⁹⁷ and an omnibus test to compare the responses of non-native and native species to each EWE⁴⁹⁸.

Sensitivity analyses

Previous studies suggested that sample outliers might influence the results of meta-analyses⁴⁹⁹. To test the robustness of our results to sample outliers, we removed those outliers and re-ran meta-analytic models to check the outcome of mean effect sizes. Outliers were classified as any standardized residual for a study whose absolute value was >3 (ref. 500) and were determined using the 'metaoutliers' function in the 'altmeta' (v.4.1) package⁵⁰¹. Neither the direction nor the significance of mean effect sizes changed when outliers were removed (see details in Supplementary Tables 8 and 9) except for the following: a significant negative response of native species to terrestrial storms became non-significant (Supplementary Table 8), and two significant positive responses (behaviour and life history traits) and one significant negative response (abundance) of native freshwater species to EWEs became non-significant (Supplementary Table 9).

To test whether the overall response to different EWEs was robust across taxa and biogeographic realms (Nearctic, Neotropic, Palaearctic, Afrotropic, Australasian) for terrestrial and freshwater species, and across provinces (Agulhas, Cold Temperate Northeast Pacific, Lusitanian, Northern European Seas, Tropical Northwestern Atlantic, Warm Temperate Northeast Pacific and Warm Temperate Northwest Atlantic) for marine species, we conducted two additional sets of sensitivity analyses specifically focusing only on those taxonomic classes and realms reporting both non-native and native animals (Supplementary Data 1).

Identifying areas of overlap between hotspots of invasions and EWEs

We finally explored overlap areas suitable for establishment of EWE-tolerant non-native animals and frequent EWEs. To achieve this, we first collected occurrence data for each non-native species and predicted their habitat suitability for establishment worldwide. We then overlapped those grids with suitable habitats for non-native species establishment with EWE hotspots (10%, 20% and 30% grids at a spatial resolution of 5 arcmin with the highest frequency of EWEs in history). For these overlapped grids, we calculated the net effect of positive, negative and neutral responses for each non-native animal to focal EWEs (that is, net effect = proportion of positive response + proportion of neutral response – proportion of negative response) on the basis of the sample effect sizes in the meta-analyses above. The accumulative net effect of EWEs on non-native species in each grid was obtained, with higher values indicating greater potential combined risks of invasions and EWEs. Details for predicting non-native species habitat suitability and the distributions of historical EWEs are summarized below.

Habitat suitability for non-native animal establishment. We first generated a non-native species list from the literature used in the meta-analysis (see non-native species list in Supplementary Data 2). Species occurrence records were then gathered from the online database of the Global Biodiversity Information Facility⁵⁰², and we added additional records from the literature (see distribution data source in Supplementary Data 2). We excluded those records without precise

coordinates and without clear establishment status. Next, we applied the 'scrubr' R package to remove duplicate coordinates⁵⁰³. For further spatial modelling analysis, occurrence data were thinned to 5-arcmin resolution (~ 9.2 km at the equator) using the 'spThin' package⁵⁰⁴ to reduce sampling bias from disproportional survey efforts among taxa or regions⁵⁰⁵. We identified the native and non-native ranges for each of species on the basis of the following databases: Global Invasive Species Database (GISD, <http://www.iucngisd.org/gisd/>), Invasive Species Compendium on CABI (<https://www.cabi.org/ISC/>), World Register of Introduced Marine Species (WRiMS, <https://www.marinespecies.org/introduced/>), SeaLifeBase (<https://www.sealifebase.se/search.php>), IUCN (<https://www.iucnredlist.org/>), and extra information from Wikipedia, Google Scholar and published literature (Supplementary Data 3). We further quantified the potential distribution of the non-native species using ecological niche modelling (ENM), which is a widely used method to provide robust predictions of potential distributions of species⁵⁰⁶. ENMs for potential species distributions under current climatic conditions were constructed using MaxEnt⁵⁰⁷ on the basis of a standard protocol following a previous study⁵⁰⁸. Details on modelling steps, predictor selection, method to account for sample bias and assessments of model performance are provided below.

ENM

To quantify potential distributions of non-native species, the MaxEnt algorithm was used to fit the models. The MaxEnt algorithm has generally shown high predictive performance and has been extensively applied in conservation, invasion and biogeography studies, and recent research shows that tuned MaxEnt models can perform comparably to ensemble models⁵⁰⁹. Training data contained both of a species' native and non-native ranges to eliminate biases in evaluating species' realized niches as some non-native species can shift their realized climatic niches in invaded areas^{510,511}. A minimum convex polygon with two-degree buffers was chosen to define the background extent where distribution occurrences of non-native species are located⁵¹². A target-group method was used to account for the potential effect of sampling bias in species occurrence data on results⁵¹³.

For land species, both climate and habitat factors including vegetation and water availability were used to predict their potential distributions, considering the important role of habitat variables in reflecting species' requirements for food and reproduction⁵¹⁴. Details on variable selection differed across taxa on the basis of their main physiological requirements following previous studies (Supplementary Table 10).

For marine non-native species, the Bio-ORACLE database (v.2.2, <https://www.bio-oracle.org/downloads-to-email.php>) was used to collect current environmental data for both surface and benthic species⁵¹⁵. Sea water depth information was accessed from Global Marine Environment Datasets (<https://gmed.auckland.ac.nz/>)⁵¹⁶. The Bio-ORACLE database supplied averaged outputs of predictors on the basis of three atmosphere–ocean general circulation models (AOGCMs) including CCSM4, HadGEM2-ES and MIROC5 at 5-arcmin (~ 9.2 km at the equator) resolution that was then used for further analyses⁵¹⁵. As climate warming effects on marine ecosystems depend on ocean depths⁵¹⁷, potential distributions of benthic and shallow-water species were predicted separately. Water depth, salinity and seasonal water temperature were necessarily used to predict distributions of benthic invertebrates and fishes^{518,519}. Specifically, a total of six candidate predictors were used to predict benthic species distributions, including water depth (m), annual mean current velocity ($\text{m}^{-1} \text{yr}^{-1}$), annual mean sea benthic salinity (PSS yr^{-1}), annual range of sea benthic salinity (PSS yr^{-1}), annual mean sea benthic temperature ($^{\circ}\text{C} \text{yr}^{-1}$) and annual range of sea benthic temperature ($^{\circ}\text{C} \text{yr}^{-1}$). For surface water fishes, water depth, sea surface temperature and salinity, and sea ice were used to predict spatial distributions^{520–522}. Potential distributions of marine surface fishes were predicted by seven candidate predictors, including water depth (m), annual mean current velocity ($\text{m}^{-1} \text{yr}^{-1}$), annual mean ice

thickness (m yr^{-1}), annual sea surface salinity (PSS yr^{-1}), annual range of sea surface salinity (PSS yr^{-1}), annual mean sea surface temperature ($^{\circ}\text{C yr}^{-1}$) and annual range of sea surface temperature ($^{\circ}\text{C yr}^{-1}$). These predictor variables did not show high correlations (Pearson's correlation coefficient $|r| < 0.70$)⁵²³.

Multiple predictor combinations from simple to full models were fitted using the MaxEnt algorithm. Cross-validations for the fitted models were performed on the basis of a spatial partitioning strategy using the 'block' method⁵²⁴. Three representative measures (area under the receiver operating characteristic curve (AUC), true skill statistic (TSS) and Boyce index) were used to evaluate the performance of fitted models^{525–527}. First, AUC is a threshold-independent measure; an AUC value between 0.7 and 0.9 indicates good model performance and a value >0.9 indicates excellent performance⁵²⁸. Second, TSS is a threshold-dependent measure with summing of sensitivity and specificity minus one⁵²⁹; a TSS value from 0.4 to 0.8 indicates good model performance and a value >0.8 indicates excellent performance. Third, the Boyce index is useful for evaluating fitted models with presence-only data to overcome potential overfitting issues. This index ranges from -1 to 1 and a higher value indicates better model performance⁵²⁷. All ENMs analyses were conducted using the 'ENMeval' package in R⁵³⁰. Overall, the ENMs used in our present study had good performance in predicting potential distributions of the non-native species (with minimum values of AUC > 0.75 ; TSS > 0.40 ; more than 83% of species with Boyce > 0.70 ; see details in Supplementary Table 11).

EWEs distribution. Distributions of different types of EWEs were collected from open data sources and publications.

Heatwave and cold-spell events on land

HadEX3 is a newly updated product generated through the coordination of the joint World Meteorological Organization (WMO) Expert Team on Climate Change Detection and Indices (ETCCDI). HadEX3 (<https://www.metoffice.gov.uk/hadobs/hadex3/>) supplies a set of 17 monthly metrics of extreme weather events gridded ($1.875^{\circ} \times 1.25^{\circ}$ longitude–latitude) for global land surfaces from 1901 to 2018 (ref. 531). Four of those metrics were selected owing to their long-term recordings by stations and representation of the frequency and intensity of thermal extremes⁵³¹. Proportions of extreme warm days and duration of warm days are commonly used to evaluate global-scale heatwave conditions^{532,533}. TX90p (percentage of time when daily maximum temperature is >90 th percentile) and WSDI (annual count when at least 6 consecutive days of maximum temperature is >90 th percentile) were used to quantify heatwave events in terrestrial and freshwater systems. TN10p (percentage of time when daily minimum temperature is <10 th percentile) and CSDI (annual count when at least 6 consecutive days of minimum temperature is <10 th percentile) were used to quantify cold-spell events.

Marine heatwave and cold-spell events

Historical marine heatwave events from 1980 to 2019 were recently reported⁵³⁴ as averaged days of heatwaves per decade at $1^{\circ} \times 1^{\circ}$ resolution at the global scale. Reference⁵³⁵ provides mean annual frequency of marine cold-spell (days) from 1982 to 2020 at $0.2498264^{\circ} \times 0.2496528^{\circ}$ resolution globally.

Storm events

The Global Risk Data Platform supplies historical recorded storm events and tracks from satellite remote-sensing from 1970 to 2015 (<https://preview.grid.unep.ch/index.php?preview=data&events=cyclones&evcat=1&lang=eng>). Available polygon layers in this platform contain information on country names, the year of storm events, starting and ending dates and the category per event. In addition, the coordinates of storm tracks per event are provided. Therefore, duration and category data of storm events at $0.5^{\circ} \times 0.5^{\circ}$ resolution were used.

Extreme flood events

Aqueduct Flood Hazard Maps provide global historical flood hazard grid datasets at $5' \times 5'$ resolution (<https://www.wri.org/data/aqueduct-floods-hazard-maps>). The historical dataset supplies times of recorded coastal and riverine floods with returning periods of 2, 5, 10, 25, 50, 100, 250 and 1,000 yr (ref. 536). Sums of times of coastal and riverine flooding events with 100-yr returning periods were used in the data analysis.

Extreme drought events

The global monthly average standardized precipitation index (SPI) dataset is available from the National Center for Atmospheric Research (NCAR)/University Corporation for Atmosphere Research (UCAR) platform (<https://www.ucar.edu/>) at $1^{\circ} \times 1^{\circ}$ resolution for the years 1942–2012. Monthly SPI is a widely used index to describe meteorological drought, and monthly SPI ≤ -1.5 was used to define an extreme drought event⁵³⁷. The SPI data for a 12-month timescale were selected to assess drought events. Furthermore, to better quantify multiple-year averages of drought events, we calculated the frequency of extreme dryness per year (that is, $(1/12) \times$ number of month(s) with SPI ≤ -1.5). The annual mean frequency of extreme dryness from January 1950 to December 2012 was used in the data analysis. We standardized all the EWEs layers with different to the same 5-arcmin resolution using the 'resample' function in the 'raster' (v.3.5-21) package⁵³⁸. Animal silhouettes in the PhyloPic database (www.phylopic.org) were accessed and visualized using the 'add_phylopic_base' function in the 'rphylopic' (v.1.1.1) package⁵³⁹. All data⁵⁴⁰ analyses were conducted in R (4.2.1)⁵⁴¹.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data have been deposited in a public structured data depository (<https://doi.org/10.6084/m9.figshare.23587695>). Source data are provided with this paper.

Code availability

The R code for running the main analyses is available at <https://doi.org/10.6084/m9.figshare.23587695>.

References

- Pyšek, P. et al. Scientists' warning on invasive alien species. *Biol. Rev.* **95**, 1511–1534 (2020).
- Urban, M. C. Accelerating extinction risk from climate change. *Science* **348**, 571–573 (2015).
- Hulme, P. E. Climate change and biological invasions: evidence, expectations, and response options. *Biol. Rev.* **92**, 1297–1313 (2017).
- Coumou, D. & Rahmstorf, S. A decade of weather extremes. *Nat. Clim. Change* **2**, 491–496 (2012).
- Harris, R. M. B. et al. Biological responses to the press and pulse of climate trends and extreme events. *Nat. Clim. Change* **8**, 579–587 (2018).
- Seneviratne, S. I. et al. in *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) 1513–1766 (IPCC, Cambridge Univ. Press, 2021).
- Smith, K. E. et al. Biological impacts of marine heatwaves. *Annu. Rev. Mar. Sci.* **15**, 119–145 (2023).
- Maxwell, S. L. et al. Conservation implications of ecological responses to extreme weather and climate events. *Divers. Distrib.* **25**, 613–625 (2019).
- Zabin, C. J. et al. Increasing the resilience of ecological restoration to extreme climatic events. *Front. Ecol. Environ.* **20**, 310–318 (2022).

10. Till, A., Rypel, A. L., Bray, A. & Fey, S. B. Fish die-offs are concurrent with thermal extremes in north temperate lakes. *Nat. Clim. Change* **9**, 637–641 (2019).
11. Wernberg, T. et al. An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nat. Clim. Change* **3**, 78–82 (2013).
12. Ameca, Y. J. E. I., Mace, G. M., Cowlshaw, G. & Pettorelli, N. Natural population die-offs: causes and consequences for terrestrial mammals. *Trends Ecol. Evol.* **27**, 272–277 (2012).
13. Sabater, S. et al. Extreme weather events threaten biodiversity and functions of river ecosystems: evidence from a meta-analysis. *Biol. Rev.* **98**, 450–461 (2023).
14. Winder, M. & Jassby, A. D. & Mac Nally, R. Synergies between climate anomalies and hydrological modifications facilitate estuarine biotic invasions. *Ecol. Lett.* **14**, 749–757 (2011).
15. Ruhí, A., Holmes, E. E., Rinne, J. N. & Sabo, J. L. Anomalous droughts, not invasion, decrease persistence of native fishes in a desert river. *Glob. Change Biol.* **21**, 1482–1496 (2015).
16. Johnston, M. W. & Purkis, S. J. Hurricanes accelerated the Florida–Bahamas lionfish invasion. *Glob. Change Biol.* **21**, 2249–2260 (2015).
17. Carlton, J. T. et al. Tsunami-driven rafting: transoceanic species dispersal and implications for marine biogeography. *Science* **357**, 1402–1405 (2017).
18. Diez, J. M. et al. Will extreme climatic events facilitate biological invasions? *Front. Ecol. Environ.* **10**, 249–257 (2012).
19. Enders, M. et al. A conceptual map of invasion biology: integrating hypotheses into a consensus network. *Glob. Ecol. Biogeogr.* **29**, 978–991 (2020).
20. Straub, S. C. et al. Resistance, extinction, and everything in between – the diverse responses of seaweeds to marine heatwaves. *Front. Mar. Sci.* <https://doi.org/10.3389/fmars.2019.00763> (2019).
21. Ehrlich, P. R. in *Ecology of Biological Invasions of North America and Hawaii* (eds Mooney, H. A. & Drake, J. A.) 79–95 (Springer, 1986).
22. Lodge, D. M. Biological invasions: lessons for ecology. *Trends Ecol. Evol.* **8**, 133–137 (1993).
23. Beauclerc, K. B., Johnson, B. & White, B. N. Genetic rescue of an inbred captive population of the critically endangered Puerto Rican crested toad (*Peltophryne lemur*) by mixing lineages. *Conserv. Genet.* **11**, 21–32 (2010).
24. Kelley, A. L. The role thermal physiology plays in species invasion. *Conserv. Physiol.* **2**, cou045 (2014).
25. Ilarri, M., Souza, A. T., Dias, E. & Antunes, C. Influence of climate change and extreme weather events on an estuarine fish community. *Sci. Total Environ.* **827**, 154190 (2022).
26. Gubanova, A. et al. Response of the Black Sea zooplankton to the marine heat wave 2010: case of the Sevastopol Bay. *J. Mar. Sci. Eng.* **10**, 1933 (2022).
27. Sorte, C. J. B., Fuller, A. & Bracken, M. E. S. Impacts of a simulated heat wave on composition of a marine community. *Oikos* **119**, 1909–1918 (2010).
28. Sanders, D., Frago, E., Kehoe, R., Patterson, C. & Gaston, K. J. A meta-analysis of biological impacts of artificial light at night. *Nat. Ecol. Evol.* **5**, 74–81 (2021).
29. Mims, M. C. & Olden, J. D. Fish assemblages respond to altered flow regimes via ecological filtering of life history strategies. *Freshw. Biol.* **58**, 50–62 (2013).
30. Pool, T. K. & Olden, J. D. Assessing long-term fish responses and short-term solutions to flow regulation in a dryland river basin. *Ecol. Freshw. Fish.* **24**, 56–66 (2015).
31. Colautti, R. I. & Lau, J. A. Contemporary evolution during invasion: evidence for differentiation, natural selection, and local adaptation. *Mol. Ecol.* **24**, 1999–2017 (2015).
32. Davidson, A. M., Jennions, M. & Nicotra, A. B. Do invasive species show higher phenotypic plasticity than native species and, if so, is it adaptive? A meta-analysis. *Ecol. Lett.* **14**, 419–431 (2011).
33. Tarusikirwa, V. L., Mutamiswa, R., English, S., Chidawanyika, F. & Nyamukondiwa, C. Thermal plasticity in the invasive South American tomato pinworm *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). *J. Therm. Biol.* **90**, 102598 (2020).
34. Magozzi, S. & Calosi, P. Integrating metabolic performance, thermal tolerance, and plasticity enables for more accurate predictions on species vulnerability to acute and chronic effects of global warming. *Glob. Change Biol.* **21**, 181–194 (2015).
35. Seebens, H. et al. No saturation in the accumulation of alien species worldwide. *Nat. Commun.* **8**, 14435 (2017).
36. Lockwood, J. L., Cassey, P. & Blackburn, T. The role of propagule pressure in explaining species invasions. *Trends Ecol. Evol.* **20**, 223–228 (2005).
37. Weaving, H., Terblanche, J. S., Pottier, P. & English, S. Meta-analysis reveals weak but pervasive plasticity in insect thermal limits. *Nat. Commun.* **13**, 5292 (2022).
38. Truhlar, A. M., Dodd, J. A. & Aldridge, D. C. Differential leaf-litter processing by native (*Gammarus pulex*) and invasive (*Dikerogammarus villosus*) freshwater crustaceans under environmental extremes. *Aquat. Conserv.* **24**, 56–65 (2014).
39. Ferreira-Rodriguez, N., Fandino, L., Pedreira, A. & Pardo, I. First evidence of asymmetric competition between the non-native clam *Corbicula fluminea* and the native freshwater mussel *Unio delphinus* during a summer heat wave. *Aquat. Conserv.* **28**, 1105–1113 (2018).
40. Dobler, A. H., Hoos, P. & Geist, J. Distribution and potential impacts of non-native Chinese pond mussels *Sinanodonta woodiana* (Lea, 1834) in Bavaria, Germany. *Biol. Invasions* **24**, 1689–1706 (2022).
41. Cook, E. J. et al. in *Aquaculture in the Ecosystem* (eds Holmer, M. et al.) 155–184 (Springer, 2008).
42. Hughes, T. P. et al. Ecological memory modifies the cumulative impact of recurrent climate extremes. *Nat. Clim. Change* **9**, 40–43 (2019).
43. Johnstone, J. F. et al. Changing disturbance regimes, ecological memory, and forest resilience. *Front. Ecol. Environ.* **14**, 369–378 (2016).
44. Howells, E. J. et al. Enhancing the heat tolerance of reef-building corals to future warming. *Sci. Adv.* **7**, eabg6070 (2021).
45. Gallagher, M. C. et al. Short-term losses and long-term gains: the non-native species *Austrominius modestus* in Lough Hyne Marine Nature Reserve. *Estuar. Coast. Shelf Sci.* **191**, 96–105 (2017).
46. David, A. A. & Simon, C. A. The effect of temperature on larval development of two non-indigenous poecilogonous polychaetes (Annelida: Spionidae) with implications for life history theory, establishment and range expansion. *J. Exp. Mar. Biol. Ecol.* **461**, 20–30 (2014).
47. Erlandsson, J., Pal, P. & McQuaid, C. D. Re-colonisation rate differs between co-existing indigenous and invasive intertidal mussels following major disturbance. *Mar. Ecol. Prog. Ser.* **320**, 169–176 (2006).
48. Donovan, M. K. et al. Local conditions magnify coral loss after marine heatwaves. *Science* **372**, 977–980 (2021).
49. Patrick, C. J. et al. A general pattern of trade-offs between ecosystem resistance and resilience to tropical cyclones. *Sci. Adv.* **8**, eabl9155 (2022).
50. Hughes, C., Richardson, C. A., Luckenbach, M. & Seed, R. Difficulties in separating hurricane induced effects from natural benthic succession: Hurricane Isabel, a case study from Eastern Virginia, USA. *Estuar. Coast. Shelf Sci.* **85**, 377–386 (2009).
51. Molnar, J. L., Gamboa, R. L., Revenga, C. & Spalding, M. D. Assessing the global threat of invasive species to marine biodiversity. *Front. Ecol. Environ.* **6**, 485–492 (2008).

52. Frölicher, T. L., Fischer, E. M. & Gruber, N. Marine heatwaves under global warming. *Nature* **560**, 360–364 (2018).
53. Studholme, J., Fedorov, A. V., Gulev, S. K., Emanuel, K. & Hodges, K. Poleward expansion of tropical cyclone latitudes in warming climates. *Nat. Geosci.* **15**, 14–28 (2022).
54. Rentschler, J., Salhab, M. & Jafino, B. A. Flood exposure and poverty in 188 countries. *Nat. Commun.* **13**, 3527 (2022).
55. Sillmann, J., Kharin, V. V., Zhang, X., Zwiers, F. W. & Bronaugh, D. Climate extremes indices in the CMIP5 multimodel ensemble: part 1. Model evaluation in the present climate. *J. Geophys. Res. Atmos.* **118**, 1716–1733 (2013).
56. Pezner, A. K. et al. Increasing hypoxia on global coral reefs under ocean warming. *Nat. Clim. Change* **13**, 403–409 (2023).
57. Magel, J. M. T., Dimoff, S. A. & Baum, J. K. Direct and indirect effects of climate change-amplified pulse heat stress events on coral reef fish communities. *Ecol. Appl.* **30**, e02124 (2020).
58. Thakur, M. P., Risch, A. C. & van der Putten, W. H. Biotic responses to climate extremes in terrestrial ecosystems. *iScience* **25**, 104559 (2022).
59. Neilson, E. W. et al. There's a storm a-coming: ecological resilience and resistance to extreme weather events. *Ecol. Evol.* **10**, 12147–12156 (2020).
60. Griffiths, K. J. Development and diapause in *Pleolophus basizonus* (Hymenoptera: Ichneumonidae). *Can. Entomol.* **101**, 907–914 (1969).
61. Brock, R. E. Occurrence and variety of fishes in mixohaline ponds of Kona, Hawaii, coast. *Copeia* **1977**, 134–139 (1977).
62. Cooke, B. D. Factors limiting the distribution of the European rabbit flea, *Spilopsyllus cuniculi* (Dale) (Siphonaptera), in inland South Australia. *Aust. J. Zool.* **32**, 493–506 (1984).
63. Dukeen, M. Y. H. & Omer, S. M. Ecology of the malaria vector *Anopheles arabiensis* Patton (Diptera, Culicidae) by the Nile in Northern Sudan. *Bull. Entomol. Res.* **76**, 451–467 (1986).
64. Cowles, T. J., Roman, M. R., Gauzens, A. L. & Copley, N. J. Short-term changes in the biology of a warm-core ring: zooplankton biomass and grazing. *Limnol. Oceanogr.* **32**, 653–664 (1987).
65. Jarvis, J. L. & Guthrie, W. D. Ecological studies of the European corn borer (Lepidoptera, Pyralidae) in Boone County, Iowa. *Environ. Entomol.* **16**, 50–58 (1987).
66. Doeg, T. J. & Koehn, J. D. Effects of draining and desilting a small weir on downstream fish and macroinvertebrates. *Regul. Rivers Res. Manag.* **9**, 263–277 (1994).
67. Dolloff, C. A., Flebbe, P. A. & Owen, M. D. Fish habitat and fish populations in a southern Appalachian watershed before and after Hurricane Hugo. *Trans. Am. Fish. Soc.* **123**, 668–678 (1994).
68. Erman, N. A. & Erman, D. C. Spring permanence, trichoptera species richness, and the role of drought. *J. Kans. Entomol. Soc.* **68**, 50–64 (1995).
69. Fitzsimons, J. M. & Nishimoto, R. T. Use of fish behavior in assessing the effects of Hurricane Iniki on the Hawaiian island of Kaua'i. *Environ. Biol. Fish.* **43**, 39–50 (1995).
70. Hogg, I. D. & Williams, D. D. Response of stream invertebrates to a global-warming thermal regime: an ecosystem-level manipulation. *Ecology* **77**, 395–407 (1996).
71. Good, W. R., Story, J. M. & Callan, N. W. Winter cold hardiness and supercooling of *Metzneria paucipunctella* (Lepidoptera: Gelechiidae), a moth introduced for biological control of spotted knapweed. *Environ. Entomol.* **26**, 1131–1135 (1997).
72. Armstrong, J. D., Braithwaite, V. A. & Fox, M. The response of wild Atlantic salmon parr to acute reductions in water flow. *J. Anim. Ecol.* **67**, 292–297 (1998).
73. Bially, A. & MacIsaac, H. J. Fouling mussels (*Dreissena* spp.) colonize soft sediments in Lake Erie and facilitate benthic invertebrates. *Freshw. Biol.* **43**, 85–97 (2000).
74. Gaines, K. F., Bryan, A. L. & Dixon, P. M. The effects of drought on foraging habitat selection of breeding wood storks in Coastal Georgia. *Waterbirds* **23**, 64–73 (2000).
75. Adams, A. J. Effects of a hurricane on two assemblages of coral reef fishes: multiple-year analysis reverses a false snapshot' interpretation. *Bull. Mar. Sci.* **69**, 341–356 (2001).
76. Bischoff, A. & Wolter, C. The flood of the century on the River Oder: effects on the 0+ fish community and implications for floodplain restoration. *Regul. Rivers Res. Manag.* **17**, 171–190 (2001).
77. Bravo, R., Soriquer, M. C., Villar, N. & Hernando, J. A. The dynamics of fish populations in the Palancar stream, a small tributary of the river Guadalquivir, Spain. *Acta Oecol.* **22**, 9–20 (2001).
78. Daltry, J. C. et al. Five years of conserving the 'world's rarest snake', the Antigua racer *Alsophis antiguae*. *Oryx* **35**, 119–127 (2001).
79. Fausch, K. D., Taniguchi, Y., Nakano, S., Grossman, G. D. & Townsend, C. R. Flood disturbance regimes influence rainbow trout invasion success among five holarctic regions. *Ecol. Appl.* **11**, 1438–1455 (2001).
80. Jones, J., DeBruyn, R. D., Barg, J. J. & Robertson, R. J. Assessing the effects of natural disturbance on a neotropical migrant songbird. *Ecology* **82**, 2628–2635 (2001).
81. Jones, K. E., Barlow, K. E., Vaughan, N., Rodríguez-Durán, A. & Gannon, M. R. Short-term impacts of extreme environmental disturbance on the bats of Puerto Rico. *Anim. Conserv.* **4**, 59–66 (2001).
82. Cheal, A. et al. Responses of coral and fish assemblages to a severe but short-lived tropical cyclone on the Great Barrier Reef, Australia. *Coral Reefs* **21**, 131–142 (2002).
83. Christman, B. J. Extreme between-year variation in productivity of a bridled titmouse (*Baeolophus wollweberi*) population. *Auk* **119**, 1149–1154 (2002).
84. Humphries, P., Serafini, L. G. & King, A. J. River regulation and fish larvae: variation through space and time. *Freshw. Biol.* **47**, 1307–1331 (2002).
85. Adams, S. M., Greeley, M. S., Law, J. M., Noga, E. J. & Zelikoff, J. T. Application of multiple sublethal stress indicators to assess the health of fish in Pamlico Sound following extensive flooding. *Estuaries* **26**, 1365–1382 (2003).
86. Bernardo, J. M., Ilheu, M., Matono, P. & Costa, A. M. Interannual variation of fish assemblage structure in a Mediterranean River: implications of streamflow on the dominance of native or exotic species. *River Res. Appl.* **19**, 521–532 (2003).
87. Covich, A. P., Crowl, T. A. & Scatena, F. N. Effects of extreme low flows on freshwater shrimps in a perennial tropical stream. *Freshw. Biol.* **48**, 1199–1206 (2003).
88. Faccio, S. D. Effects of ice storm-created gaps on forest breeding bird communities in central Vermont. *Ecol. Manag.* **186**, 133–145 (2003).
89. Gaillard, J. M. et al. Effects of hurricane Lothar on the population dynamics of European roe deer. *J. Wildl. Manag.* **67**, 767–773 (2003).
90. Adams, A. J. & Ebersole, J. P. Resistance of coral reef fishes in back reef and lagoon habitats to a hurricane. *Bull. Mar. Sci.* **75**, 101–113 (2004).
91. Chen, L.-H., Chu, K. C.-M. & Chiu, Y.-W. Impacts of natural disturbance on fish communities in the Tachia River, Taiwan. *Hydrobiologia* **522**, 149–164 (2004).
92. Herremans, M. Effects of drought on birds in the Kalahari, Botswana. *Ostrich* **75**, 217–227 (2004).
93. Hurd, L. E., Mallis, R. E., Bulka, K. C. & Jones, A. M. Life history, environment, and deme extinction in the Chinese mantid *Tenodera aridifolia sinensis* (Mantodea: Mantidae). *Environ. Entomol.* **33**, 182–187 (2004).
94. Bolger, D. T., Patten, M. A. & Bostock, D. C. Avian reproductive failure in response to an extreme climatic event. *Oecologia* **142**, 398–406 (2005).

95. Bouget, C. & Noblecourt, T. Short-term development of ambrosia and bark beetle assemblages following a windstorm in French broadleaved temperate forests. *J. Appl. Entomol.* **129**, 300–310 (2005).
96. Chan, K. S., Mysterud, A., Oritsland, N. A., Severinsen, T. & Stenseth, N. C. Continuous and discrete extreme climatic events affecting the dynamics of a high-arctic reindeer population. *Oecologia* **145**, 556–563 (2005).
97. Echeverria, C. A., Paiva, P. C. & Alves, V. C. Composition and biomass of shallow benthic megafauna during an annual cycle in Admiralty Bay, King George Island, Antarctica. *Antarct. Sci.* **17**, 312–318 (2005).
98. Barko, V. A., Herzog, D. P. & O'Connell, M. T. Response of fishes to floodplain connectivity during and following a 500-year flood event in the unimpounded upper Mississippi River. *Wetlands* **26**, 244–257 (2006).
99. Bushek, D. & Boyd, S. Seasonal abundance and occurrence of the Asian isopod *Synidotea laevidorsalis* in Delaware Bay, USA. *Biol. Invasions* **8**, 697–702 (2006).
100. Dodd, C. K. Jr., Ozgul, A. & Oli, M. K. The influence of disturbance events on survival and dispersal rates of Florida box turtles. *Ecol. Appl.* **16**, 1936–1944 (2006).
101. Esselstyn, J. A., Amar, A. & Janeke, D. Impact of post-typhoon hunting on Mariana fruit bats (*Pteropus mariannus*). *Pac. Sci.* **60**, 531–539 (2006).
102. Fields, P. A., Rudomin, E. L. & Somero, G. N. Temperature sensitivities of cytosolic malate dehydrogenases from native and invasive species of marine mussels (genus *Mytilus*): sequence-function linkages and correlations with biogeographic distribution. *J. Exp. Biol.* **209**, 656–667 (2006).
103. Jurajda, P., Reichard, M. & Smith, C. Immediate impact of an extensive summer flood on the adult fish assemblage of a channelized lowland river. *J. Freshw. Ecol.* **21**, 493–501 (2006).
104. Budy, P., Thiede, G. P. & McHugh, P. Quantification of the vital rates, abundance, and status of a critical, endemic population of Bonneville cutthroat trout. *North Am. J. Fish. Manag.* **27**, 593–604 (2007).
105. Cromer, R. B., Gresham, C. A., Goddard, M., Landham, J. D. & Hanlin, H. G. Associations between two bottomland hardwood forest shrew species and hurricane-generated woody debris. *Southeast. Nat.* **6**, 235–246 (2007).
106. Dewson, Z. S., James, A. B. W. & Death, R. G. Invertebrate community responses to experimentally reduced discharge in small streams of different water quality. *J. North Am. Benthol. Soc.* **26**, 754–766 (2007).
107. Fenoglio, S., Bo, T., Cucco, M. & Malacarne, G. Response of benthic invertebrate assemblages to varying drought conditions in the Po river (NW Italy). *Ital. J. Zool.* **74**, 191–201 (2007).
108. Budy, P., Thiede, G. P., McHugh, P., Hansen, E. S. & Wood, J. Exploring the relative influence of biotic interactions and environmental conditions on the abundance and distribution of exotic brown trout (*Salmo trutta*) in a high mountain stream. *Ecol. Freshw. Fish.* **17**, 554–566 (2008).
109. Cardoso, P. G., Raffaelli, D. & Pardal, M. A. The impact of extreme weather events on the seagrass *Zostera noltii* and related *Hydrobia ulvae* population. *Mar. Pollut. Bull.* **56**, 483–492 (2008).
110. Chuang, L. C., Shieh, B.-S., Liu, C.-C., Lin, Y.-S. & Liang, S.-H. Effects of typhoon disturbance on the abundances of two mid-water fish species in a mountain stream of northern Taiwan. *Zool. Stud.* **47**, 564–573 (2008).
111. Dionne, M., Maurice, C., Gauthier, J. & Shaffer, F. Impact of Hurricane Wilma on migrating birds: the case of the Chimney Swift. *Wilson J. Ornithol.* **120**, 784–792 (2008).
112. Dodd, C. K. Jr. & Dreslik, M. J. Habitat disturbances differentially affect individual growth rates in a long-lived turtle. *J. Zool.* **275**, 18–25 (2008).
113. Fair, J. M. & Whitaker, S. J. Avian cell-mediated immune response to drought. *Wilson J. Ornithol.* **120**, 813–819 (2008).
114. Frederiksen, M., Daunt, F., Harris, M. P. & Wanless, S. The demographic impact of extreme events: stochastic weather drives survival and population dynamics in a long-lived seabird. *J. Anim. Ecol.* **77**, 1020–1029 (2008).
115. Freeman, A. N. D., Pias, K. & Vinson, M. F. The impact of Tropical Cyclone Larry on bird communities in fragments of the endangered rainforest Type 5b. *Austral Ecol.* **33**, 532–540 (2008).
116. Gandhi, K. J. K. et al. Catastrophic windstorm and fuel-reduction treatments alter ground beetle (Coleoptera: Carabidae) assemblages in a North American sub-boreal forest. *Ecol. Manag.* **256**, 1104–1123 (2008).
117. Haag, W. R. & Warren, M. L. Jr. Effects of severe drought on freshwater mussel assemblages. *Trans. Am. Fish. Soc.* **137**, 1165–1178 (2008).
118. Bêche, L. A., Connors, P. G., Resh, V. H. & Merenlender, A. M. Resilience of fishes and invertebrates to prolonged drought in two California streams. *Ecography* **32**, 778–788 (2009).
119. Champeau, T. R., Stevens, P. W. & Blewett, D. A. Comparison of fish community metrics to assess long-term changes and hurricane impacts at Peace River, Florida. *Fla. Sci.* **72**, 289–309 (2009).
120. Dessaix, J. & Fruget, J. F. Long-term changes in the Crustaceans fauna of the Middle Rhone River consequently to hydroclimatic events. *Hydroecol. Appl.* **16**, 1–27 (2009).
121. Devney, C. A., Short, M. & Congdon, B. C. Cyclonic and anthropogenic influences on tern populations. *Wildl. Res.* **36**, 368–378 (2009).
122. Fleming, T. H. & Murray, K. L. Population and genetic consequences of hurricanes for three species of west indian phyllostomid bats. *Biotropica* **41**, 250–256 (2009).
123. Fleming, T. H., Murray, K. L. & Carstens, B. *Phylogeography and Genetic Structure of Three Evolutionary Lineages of West Indian Phyllostomid Bats. Island Bats: Evolution, Ecology, and Conservation* (eds Fleming, T. H. & Racey, P. A.) 116–150 (Univ. Chicago Press, 2009).
124. Garrabou, J. et al. Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Glob. Change Biol.* **15**, 1090–1103 (2009).
125. Hopton, M. E., Cameron, G. N., Cramer, M. J., Polak, M. & Uetz, G. W. Live animal radiography to measure developmental instability in populations of small mammals after a natural disaster. *Ecol. Indic.* **9**, 883–891 (2009).
126. Ilg, C., Foeckler, F., Deichner, O. & Henle, K. Extreme flood events favour floodplain mollusc diversity. *Hydrobiologia* **621**, 63–73 (2009).
127. Balayla, D., Lauridsen, T. L., Søndergaard, M. & Jeppesen, E. Larger zooplankton in Danish lakes after cold winters: are winter fish kills of importance? *Hydrobiologia* **646**, 159–172 (2010).
128. Charruau, P., Thorbjarnarson, J. B. & Hénaut, Y. Tropical cyclones and reproductive ecology of *Crocodylus acutus* Cuvier, 1807 (Reptilia: Crocodylia: Crocodylidae) on a Caribbean atoll in Mexico. *J. Nat. Hist.* **44**, 741–761 (2010).
129. Chebbi, N., Mastrototaro, F. & Missaoui, H. Spatial distribution of ascidians in two Tunisian lagoons of the Mediterranean Sea. *Cah. Biol. Mar.* **51**, 117–127 (2010).
130. Costelloe, J. F. et al. Are alien fish disadvantaged by extremely variable flow regimes in arid-zone rivers? *Mar. Freshw. Res.* **61**, 857–863 (2010).
131. Gunzburger, M. S., Hughes, W. B., Barichivich, W. J. & Staiger, J. S. Hurricane storm surge and amphibian communities in coastal wetlands of northwestern Florida. *Wetl. Ecol. Manag.* **18**, 651–663 (2010).
132. Aymi, R., Rodriguez, M. & Cama, A. Influx of kittiwakes *Rissa tridactyla* into Catalonia (NE Spain) in January 2009 and a review of previous records. *Rev. Catalana Ornitol.* **27**, 17–24 (2011).

133. Brown, D. R., Sherry, T. W. & Harris, J. Hurricane Katrina impacts the breeding bird community in a bottomland hardwood forest of the Pearl River Basin, Louisiana. *Ecol. Manag.* **261**, 111–119 (2011).
134. Cane, J. H. & Neff, J. L. Predicted fates of ground-nesting bees in soil heated by wildfire: thermal tolerances of life stages and a survey of nesting depths. *Biol. Conserv.* **144**, 2631–2636 (2011).
135. Canning-Clode, J., Fowler, A. E., Byers, J. E., Carlton, J. T. & Ruiz, G. M. ‘Caribbean Creep’ chills out: climate change and marine invasive species. *PLoS ONE* <https://doi.org/10.1371/journal.pone.0029657> (2011).
136. Cochran, P. A. & Stagg, T. W. Response of a fish assemblage to severe flooding in Gilmore Creek, a southeastern Minnesota trout stream. *J. Freshw. Ecol.* **26**, 77–84 (2011).
137. Convertino, M. et al. Do tropical cyclones shape shorebird habitat patterns? Biogeoclimatology of snowy plovers in Florida. *PLoS ONE* **6**, e15683 (2011).
138. Diaz Villanueva, V., Albarino, R. & Canhoto, C. Detritivores feeding on poor quality food are more sensitive to increased temperatures. *Hydrobiologia* **678**, 155–165 (2011).
139. Firth, L. B., Knights, A. M. & Bell, S. S. Air temperature and winter mortality: implications for the persistence of the invasive mussel, *Perna viridis* in the intertidal zone of the south-eastern United States. *J. Exp. Mar. Biol. Ecol.* **400**, 250–256 (2011).
140. Franzke, A. & Reinhold, K. Stressing food plants by altering water availability affects grasshopper performance. *Ecosphere* **2**, 1–13 (2011).
141. Johnson, S. E. et al. Gray-headed lemur (*Eulemur cinereiceps*) abundance and forest structure dynamics at Manombo, Madagascar. *Biotropica* **43**, 371–379 (2011).
142. Adamo, S. A., Baker, J. L., Lovett, M. M. E. & Wilson, G. Climate change and temperate zone insects: the tyranny of thermodynamics meets the world of limited resources. *Environ. Entomol.* **41**, 1644–1652 (2012).
143. Ammunet, T., Kaukoranta, T., Saikkonen, K., Repo, T. & Klemola, T. Invading and resident defoliators in a changing climate: cold tolerance and predictions concerning extreme winter cold as a range-limiting factor. *Ecol. Entomol.* **37**, 212–220 (2012).
144. Buerger, L. P. & Mills, N. J. Ecologically relevant measures of the physiological tolerance of light brown apple moth, *Epiphyas postvittana*, to high temperature extremes. *J. Insect Physiol.* **58**, 1184–1191 (2012).
145. Dodd, C. K. Jr., Hyslop, N. L. & Oli, M. K. The effects of disturbance events on abundance and sex ratios of a terrestrial turtle, *Terrapene bauri*. *Chelonian Conserv. Biol.* **11**, 44–49 (2012).
146. Elmer, A., Lane, J., Summerville, K. S. & Lown, L. Does low-density grazing affect butterfly (Lepidoptera) colonization of a previously flooded tallgrass prairie reconstruction? *Gt. Lakes Entomol.* **45**, 69–78 (2012).
147. Feeley, H. B., Davis, S., Bruen, M., Blacklocke, S. & Kelly-Quinn, M. The impact of a catastrophic storm event on benthic macroinvertebrate communities in upland headwater streams and potential implications for ecological diversity and assessment of ecological status. *J. Limnol.* **71**, 299–308 (2012).
148. Angelidis, A. *Fulvia fragilis* (Forsskal in Niebuhr, 1775) (Bivalvia: Cardiidae), first record of an alien mollusk in the Gulf of Thessaloniki (Inner Thermaikos Gulf, North Aegean Sea, Greece). *J. Biol. Res.* **20**, 228–232 (2013).
149. Apodaca, J. J., Trexler, J. C., Jue, N. K., Schrader, M. & Travis, J. Large-scale natural disturbance alters genetic population structure of the sailfin molly, *Poecilia latipinna*. *Am. Nat.* **181**, 254–263 (2013).
150. Banko, P. C. et al. Response of palila and other subalpine Hawaiian forest bird species to prolonged drought and habitat degradation by feral ungulates. *Biol. Conserv.* **157**, 70–77 (2013).
151. Brouwers, N., Matusick, G., Ruthrof, K., Lyons, T. & Hardy, G. Landscape-scale assessment of tree crown dieback following extreme drought and heat in a Mediterranean eucalypt forest ecosystem. *Landsc. Ecol.* **28**, 69–80 (2013).
152. Burk, R. A. & Kennedy, J. H. Invertebrate communities of groundwater-dependent refugia with varying hydrology and riparian cover during a suprasedasonal drought. *J. Freshw. Ecol.* **28**, 251–270 (2013).
153. Cayetano, L. & Vorburger, C. Effects of heat shock on resistance to parasitoids and on life history traits in an aphid/endosymbiont system. *PLoS ONE* <https://doi.org/10.1371/journal.pone.0075966> (2013).
154. Churchill, C. J. Spatio-temporal spawning and larval dynamics of a zebra mussel (*Dreissena polymorpha*) population in a North Texas Reservoir: implications for invasions in the southern United States. *Aquat. Invasions* **8**, 389–406 (2013).
155. Clarke, M. W., Thompson, G. J. & Sinclair, B. J. Cold tolerance of the eastern subterranean termite, *Reticulitermes flavipes* (Isoptera: Rhinotermitidae), in Ontario. *Environ. Entomol.* **42**, 805–810 (2013).
156. Dodd, C. K. *Frogs of the United States and Canada* (Johns Hopkins Univ. Press, 2013).
157. Dowd, W. W. & Somero, G. N. Behavior and survival of *Mytilus* congeners following episodes of elevated body temperature in air and seawater. *J. Exp. Biol.* **216**, 502–514 (2013).
158. Esselman, P. C., Schmitter-Soto, J. J. & Allan, J. D. Spatiotemporal dynamics of the spread of African tilapias (Pisces: *Oreochromis* spp.) into rivers of northeastern Mesoamerica. *Biol. Invasions* **15**, 1471–1491 (2013).
159. Fiedler, P. C. et al. Effects of a tropical cyclone on a pelagic ecosystem from the physical environment to top predators. *Mar. Ecol. Prog. Ser.* **484**, 1–16 (2013).
160. Fobert, E. et al. Predicting non-native fish dispersal under conditions of climate change: case study in dynamics of dispersal and establishment of pumpkinseed *Lepomis gibbosus* in a floodplain pond. *Ecol. Freshw. Fish.* **22**, 106–116 (2013).
161. Frank, K. L., Tobin, P. C., Thistle, H. W. Jr. & Kalkstein, L. S. Interpretation of gypsy moth frontal advance using meteorology in a conditional algorithm. *Int. J. Biometeorol.* **57**, 459–473 (2013).
162. Genovart, M. et al. Contrasting effects of climatic variability on the demography of a trans-equatorial migratory seabird. *J. Anim. Ecol.* **82**, 121–130 (2013).
163. Hocking, D. J., Babbitt, K. J. & Yamasaki, M. Comparison of silvicultural and natural disturbance effects on terrestrial salamanders in northern hardwood forests. *Biol. Conserv.* **167**, 194–202 (2013).
164. Jessop, T. S., Letnic, M., Webb, J. K. & Dempster, T. Adrenocortical stress responses influence an invasive vertebrate’s fitness in an extreme environment. *Proc. R. Soc. B* <https://doi.org/10.1098/rspb.2013.1444> (2013).
165. Ju, R.-T., Gao, L., Zhou, X.-H. & Li, B. Tolerance to high temperature extremes in an invasive lace bug, *Corythucha ciliata* (Hemiptera: Tingidae), in subtropical China. *PLoS ONE* <https://doi.org/10.1371/journal.pone.0054372> (2013).
166. Alford, L., Andrade, T. O., Georges, R., Burel, F. & van Baaren, J. Could behaviour and not physiological thermal tolerance determine winter survival of aphids in cereal fields? *PLoS ONE* <https://doi.org/10.1371/journal.pone.0114982> (2014).
167. Arula, T., Ojaveer, H. & Klais, R. Impact of extreme climate and bioinvasion on temporal coupling of spring herring (*Clupea harengus* m.) larvae and their prey. *Mar. Environ. Res.* **102**, 102–109 (2014).
168. Bauerfeind, S. S. & Fischer, K. Simulating climate change: temperature extremes but not means diminish performance in a widespread butterfly. *Popul. Ecol.* **56**, 239–250 (2014).

169. Boersma, K. S., Bogan, M. T., Henrichs, B. A. & Lytle, D. A. Invertebrate assemblages of pools in arid-land streams have high functional redundancy and are resistant to severe drying. *Freshw. Biol.* **59**, 491–501 (2014).
170. Bogan, M. T. et al. Biogeography and conservation of aquatic fauna in spring-fed tropical canyons of the southern Sonoran Desert, Mexico. *Biodivers. Conserv.* **23**, 2705–2748 (2014).
171. Bologna, P. A. X. Mangrove loss leads to fish hyperutilization of seagrass beds in a UNESCO biosphere reserve. *J. Fish. Biol.* **84**, 1620–1625 (2014).
172. Brown, C. R. & Brown, M. B. Breeding time in a migratory songbird is predicted by drought severity and group size. *Ecology* **95**, 2736–2744 (2014).
173. Calapez, A. R., Elias, C. L., Almeida, S. F. P. & Feio, M. J. Extreme drought effects and recovery patterns in the benthic communities of temperate streams. *Limnetica* **33**, 281–296 (2014).
174. Deville, A. S. et al. Impacts of extreme climatic events on the energetics of long-lived vertebrates: the case of the greater flamingo facing cold spells in the Camargue. *J. Exp. Biol.* **217**, 3700–3707 (2014).
175. Eash-Loucks, W. E., Kimball, M. E. & Petrinc, K. M. Long-term changes in an estuarine mud crab community: evaluating the impact of non-native species. *J. Crustac. Biol.* **34**, 731–738 (2014).
176. Faulkner, K. T., Clusella-Trullas, S., Peck, L. S. & Chown, S. L. Lack of coherence in the warming responses of marine crustaceans. *Funct. Ecol.* **28**, 895–903 (2014).
177. Fischer, K., Klockmann, M. & Reim, E. Strong negative effects of simulated heat waves in a tropical butterfly. *J. Exp. Biol.* **217**, 2892–2898 (2014).
178. Gerisch, M. Non-random patterns of functional redundancy revealed in ground beetle communities facing an extreme flood event. *Funct. Ecol.* **28**, 1504–1512 (2014).
179. Andraca-Gomez, G. et al. A potential invasion route of *Cactoblastis cactorum* within the Caribbean region matches historical hurricane trajectories. *Biol. Invasions* **17**, 1397–1406 (2015).
180. Andriuzzi, W. S., Pulleman, M. M., Schmidt, O., Faber, J. H. & Brussaard, L. Anecic earthworms (*Lumbricus terrestris*) alleviate negative effects of extreme rainfall events on soil and plants in field mesocosms. *Plant Soil* **397**, 103–113 (2015).
181. Bateman, B. L. et al. The importance of range edges for an irruptive species during extreme weather events. *Landsc. Ecol.* **30**, 1095–1110 (2015).
182. Ellender, B. R. & Weyl, O. L. F. Resilience of imperilled headwater stream fish to an unpredictable high-magnitude flood. *Koedoe* **57**, a1258 (2015).
183. Gardner, P. G., Frazer, T. K., Jacoby, C. A. & Yanong, R. P. E. Reproductive biology of invasive lionfish (*Pterois* spp.). *Front. Mar. Sci.* <https://doi.org/10.3389/fmars.2015.00007> (2015).
184. Aborgiba, M. et al. Flooding modifies the genotoxic effects of pollution on a worm, a mussel and two fish species from the Sava River. *Sci. Total Environ.* **540**, 358–367 (2016).
185. Bielen, A. et al. Differences in tolerance to anthropogenic stress between invasive and native bivalves. *Sci. Total Environ.* **543**, 449–459 (2016).
186. Downing, J., Borrero, H. & Liu, H. Differential impacts from an extreme cold spell on subtropical vs. tropical specialist bees in southern Florida. *Ecosphere* **7**, e01302 (2016).
187. Esperk, T., Kjærsgaard, A., Walters, R. J., Berger, D. & Blanckenhorn, W. U. Plastic and evolutionary responses to heat stress in a temperate dung fly: negative correlation between basal and induced heat tolerance? *J. Evol. Biol.* **29**, 900–915 (2016).
188. Foord, S. H. & Fouche, P. S. O. Response of instream animal communities to a short-term extreme event and to longer-term cumulative impacts in a strategic water resource area, South Africa. *Afr. J. Aquat. Sci.* **41**, 29–40 (2016).
189. Foucreau, N., Piscart, C., Puijalon, S. & Hervant, F. Effects of rising temperature on a functional process: consumption and digestion of leaf litter by a freshwater shredder. *Fundam. Appl. Limnol.* **187**, 295–306 (2016).
190. Grossman, G. D., Sundin, G. & Ratajczak, R. E. Jr. Long-term persistence, density dependence and effects of climate change on rosyside dace (Cyprinidae). *Freshw. Biol.* **61**, 832–847 (2016).
191. James, D. G. Population biology of monarch butterflies, *Danaus plexippus* (L.) (Lepidoptera: Nymphalidae), at a milkweed-rich summer breeding site in central Washington. *J. Lepid. Soc.* **70**, 182–193 (2016).
192. Jones, A. R. et al. Tick exposure and extreme climate events impact survival and threaten the persistence of a long-lived lizard. *J. Anim. Ecol.* **85**, 598–610 (2016).
193. Adams, A. J. et al. Extreme drought, host density, sex, and bullfrogs influence fungal pathogen infection in a declining lotic amphibian. *Ecosphere* **8**, e01740 (2017).
194. Benkwitt, C. E. et al. Is the lionfish invasion waning? Evidence from the Bahamas. *Coral Reefs* **36**, 1255–1261 (2017).
195. Carreira, B. M., Segurado, P., Laurila, A. & Rebelo, R. Can heat waves change the trophic role of the world's most invasive crayfish? Diet shifts in *Procambarus clarkii*. *PLoS ONE* <https://doi.org/10.1371/journal.pone.0183108> (2017).
196. Dodds, K. J., Hanavan, R. P. & DiGirolomo, M. F. Firewood collected after a catastrophic wind event: the bark beetle (Scolytinae) and woodborer (Buprestidae, Cerambycidae) community present over a 3-year period. *Agric. Entomol.* **19**, 309–320 (2017).
197. Glasheen, P. M., Calvo, C., Meerhoff, M., Hayes, K. A. & Burks, R. L. Survival, recovery, and reproduction of apple snails (*Pomacea* spp.) following exposure to drought conditions. *Freshw. Sci.* **36**, 316–324 (2017).
198. Andrade, J. T. M. et al. Effect of temperature on behavior, glycogen content, and mortality in *Limnoperna fortunei* (Dunker, 1857) (Bivalvia: Mytilidae). *J. Limnol.* **77**, 189–198 (2018).
199. Banahene, N. et al. Thermal sensitivity of gypsy moth (Lepidoptera: Erebidae) during larval and pupal development. *Environ. Entomol.* **47**, 1623–1631 (2018).
200. Beaver, J. R. et al. Long-term trends in seasonal plankton dynamics in Lake Mead (Nevada-Arizona, USA) and implications for climate change. *Hydrobiologia* **822**, 85–109 (2018).
201. Bino, G., Wassens, S., Kingsford, R. T., Thomas, R. F. & Spencer, J. Floodplain ecosystem dynamics under extreme dry and wet phases in semi-arid Australia. *Freshw. Biol.* **63**, 224–241 (2018).
202. Burnett, J. L. et al. Thermal tolerance limits of the Chinese mystery snail (*Bellamya chinensis*): implications for management. *Am. Malacol. Bull.* **36**, 140–144 (2018).
203. Chen, H. et al. Effect of short-term high-temperature exposure on the life history parameters of *Ophraella communa*. *Sci. Rep.* **8**, 13969 (2018).
204. Cira, T. M., Koch, R. L., Burkness, E. C., Hutchison, W. D. & Venette, R. C. Effects of diapause on *Halyomorpha halys* (Hemiptera: Pentatomidae) cold tolerance. *Environ. Entomol.* **47**, 997–1004 (2018).
205. Cuddington, K., Sobek-Swant, S., Crosthwaite, J. C., Lyons, D. B. & Sinclair, B. J. Probability of emerald ash borer impact for Canadian cities and North America: a mechanistic model. *Biol. Invasions* **20**, 2661–2677 (2018).
206. Dhawan, R., Fischhoff, I. R. & Ostfeld, R. S. Effects of weather variability on population dynamics of white-footed mice (*Peromyscus leucopus*) and eastern chipmunks (*Tamias striatus*). *J. Mammal.* **99**, 1436–1443 (2018).
207. Drouillard, K. G. et al. Comparison of thermal tolerance and standard metabolic rate of two Great Lakes invasive fish species. *J. Great Lakes Res.* **44**, 476–481 (2018).

208. Eben, A., Reifenrath, M., Briem, F., Pink, S. & Vogt, H. Response of *Drosophila suzukii* (Diptera: Drosophilidae) to extreme heat and dryness. *Agric. Entomol.* **20**, 113–121 (2018).
209. Egly, R. M. & Larson, E. R. Distribution, habitat associations, and conservation status updates for the pilose crayfish *Pacifastacus gambelii* (Girard, 1852) and Snake River pilose crayfish *Pacifastacus connectens* (Faxon, 1914) of the western United States. *PeerJ* **6**, e5668 (2018).
210. Ferreira-Rodriguez, N., Fernandez, I., Leonor Cancela, M. & Pardo, I. Multibiome response shows how native and non-native freshwater bivalves differentially cope with heat-wave events. *Aquat. Conserv.* **28**, 934–943 (2018).
211. Ha, G. & Williams, S. L. Eelgrass community dominated by native omnivores in Bodega Bay, California, USA. *Bull. Mar. Sci.* **94**, 1333–1353 (2018).
212. Hossain, M. Y., Vadas, R. L. Jr., Ruiz-Carus, R. & Galib, S. M. Amazon sailfin catfish *Pterygoplichthys pardalis* (Loricariidae) in Bangladesh: a critical review of its invasive threat to native and endemic aquatic species. *Fishes* **3**, 14 (2018).
213. Adams, P. J., Fontaine, J. B., Huston, R. M. & Fleming, P. A. Quantifying efficacy of feral pig (*Sus scrofa*) population management. *Wildl. Res.* **46**, 587–598 (2019).
214. Arafeh-Dalmau, N. et al. Extreme marine heatwaves alter kelp forest community near its equatorward distribution limit. *Front. Mar. Sci.* <https://doi.org/10.3389/fmars.2019.00499> (2019).
215. Barbosa, A. C. C., Vinagre, C., Mizrahi, D. & Flores, A. A. V. Temperature-driven secondary competence windows may increase the dispersal potential of invasive sun corals. *Mar. Biol.* **166**, 131 (2019).
216. Behn, K. E. & Baxter, C. V. The trophic ecology of a desert river fish assemblage: influence of season and hydrologic variability. *Ecosphere* **10**, e02583 (2019).
217. Byrd, B. D. et al. Aquatic thermal conditions predict the presence of native and invasive rock pool *Aedes* (Diptera: Culicidae) in the southern Appalachians, USA. *J. Vector Ecol.* **44**, 30–39 (2019).
218. Dodds, W. K. & Whiles, M. R. *Freshwater Ecology: Concepts and Environmental Applications of Limnology* 3rd edn (Academic Press, 2019).
219. Ferreira-Rodriguez, N. Spatial aggregation of native with non-native freshwater bivalves and activity depletion under summer heat waves: ‘dangerous liaisons’ in a climate change context. *Hydrobiologia* **834**, 75–85 (2019).
220. Herbst, D. B., Cooper, S. D., Medhurst, R. B., Wiseman, S. W. & Hunsaker, C. T. Drought ecohydrology alters the structure and function of benthic invertebrate communities in mountain streams. *Freshw. Biol.* **64**, 886–902 (2019).
221. Andraca-Gomez, G. et al. Local dispersal pathways during the invasion of the cactus moth, *Cactoblastis cactorum*, within North America and the Caribbean. *Sci. Rep.* **10**, 11012 (2020).
222. Archdeacon, T. P., Diver-Franssen, T. A., Bertrand, N. G. & Grant, J. D. Drought results in recruitment failure of Rio Grande silvery minnow (*Hybognathus amarus*), an imperiled, pelagic broadcast-spawning minnow. *Environ. Biol. Fish.* **103**, 1033–1044 (2020).
223. Bonsignore, C. P., Vizzari, G., Vono, G. & Bernardo, U. Short-term cold stress affects parasitism on the Asian chestnut gall wasp *Dryocosmus kuriphilus*. *Insects* **11**, 841 (2020).
224. Cruz, D. O. et al. Connectivity but not recruitment: response of the fish community to a large-scale flood on a heavily regulated floodplain. *Ecohydrology* **13**, e2194 (2020).
225. Dobosenski, J. A., Strasburg, J. L., Larson, W. A. & Hrabik, T. R. Investigating population genetics of invasive rainbow smelt in the Great Lakes Region. *J. Gt. Lakes Res.* **46**, 382–390 (2020).
226. Enriquez-Urzelai, U. et al. The roles of acclimation and behaviour in buffering climate change impacts along elevational gradients. *J. Anim. Ecol.* **89**, 1722–1734 (2020).
227. Fiala, T. et al. *Xylosandrus germanus* in Central Europe: spread into and within the Czech Republic. *J. Appl. Entomol.* **144**, 423–433 (2020).
228. Fokidis, H. B. & Brock, T. Hurricane Irma induces divergent behavioral and hormonal impacts on an urban and forest population of invasive *Anolis* lizards: evidence for an urban resilience hypothesis. *J. Urban Ecol.* **6**, juaa031 (2020).
229. Hopper, G. W. et al. Nowhere to swim: interspecific responses of prairie stream fishes in isolated pools during severe drought. *Aquat. Sci.* **82**, 42 (2020).
230. Hopper, G. W. et al. Biomass loss and change in species dominance shift stream community excretion stoichiometry during severe drought. *Freshw. Biol.* **65**, 403–416 (2020).
231. Hraoui, G., Bettinazzi, S., Gendron, A. D., Boisclair, D. & Breton, S. Mitochondrial thermo-sensitivity in invasive and native freshwater mussels. *J. Exp. Biol.* **223**, jeb215921 (2020).
232. Huang, Y. et al. Effect of short-term high temperatures on the growth, development and reproduction in the fruit fly, *Bactrocera tau* (Diptera: Tephritidae). *Sci. Rep.* **10**, 6418 (2020).
233. Barbosa, S. Is a handful of genes responsible for the common starling invasion success? *Mol. Ecol.* **30**, 1361–1363 (2021).
234. Buchsbaum, R. Responses and recovery of salt marsh vegetation and birds in southeastern Massachusetts to two hydrologic events: a tidal restoration and an inundation event. *Estuaries Coasts* **44**, 2132–2141 (2021).
235. Castro, N. et al. Winners and losers: prevalence of non-indigenous species under simulated marine heatwaves and high propagule pressure. *Mar. Ecol. Prog. Ser.* **668**, 21–38 (2021).
236. Claunch, N. M. et al. Invaders from islands: thermal matching, potential or flexibility? *Biol. J. Linn. Soc.* **134**, 587–603 (2021).
237. Couper, L. I., Sanders, N. J., Heller, N. E. & Gordon, D. M. Multiyear drought exacerbates long-term effects of climate on an invasive ant species. *Ecology* **102**, e03476 (2021).
238. Crespo, D. et al. Does an invasive bivalve outperform its native congener in a heat wave scenario? A laboratory study case with *Ruditapes decussatus* and *R. philippinarum*. *Biology* **10**, 1284 (2021).
239. Dahl, J. E. et al. Thermal plasticity and sensitivity to insecticides in populations of an invasive beetle: cyfluthrin increases vulnerability to extreme temperature. *Chemosphere* **274**, 129905 (2021).
240. Gilson, A. R., Coughlan, N. E., Dick, J. T. A. & Kregting, L. Marine heat waves differentially affect functioning of native (*Ostrea edulis*) and invasive (*Crassostrea Magallana gigas*) oysters in tidal pools. *Mar. Environ. Res.* **172**, 105497 (2021).
241. Heath, J. A., Kochert, M. N. & Steenhof, K. Golden eagle dietary shifts following wildfire and shrub loss have negative consequences for nestling survivorship. *Ornithol. Appl.* **123**, duab034 (2021).
242. Islam, M. J., Kunzmann, A. & Slater, M. J. Extreme winter cold-induced osmoregulatory, metabolic, and physiological responses in European seabass (*Dicentrarchus labrax*) acclimatized at different salinities. *Sci. Total Environ.* **771**, 145202 (2021).
243. Ashe-Jepson, E. et al. Oviposition behaviour and emergence through time of the small blue butterfly (*Cupido minimus*) in a nature reserve in Bedfordshire, UK. *J. Insect Conserv.* **26**, 43–58 (2022).
244. Cerrilla, C. et al. Rapid population decline in one of the last recruiting populations of the endangered Clanwilliam sandfish (*Labeo seeberi*): the roles of climate change and non-native fish. *Aquat. Conserv.* **32**, 781–796 (2022).
245. De Jesus, A. D. & Jimenez, A. G. Effects of acute temperature increases on house sparrow (*Passer domesticus*) pectoralis muscle myonuclear domain. *J. Exp. Zool. A* **337**, 150–158 (2022).

246. Duell, M. E., Gray, M. T., Roe, A. D., MacQuarrie, C. J. K. & Sinclair, B. J. Plasticity drives extreme cold tolerance of emerald ash borer (*Agrilus planipennis*) during a polar vortex. *Curr. Res. Insect Sci.* **2**, 100031 (2022).
247. Messenger, P. S. & Flitters, N. E. Bioclimatic studies of 3 species of fruit flies in Hawaii. *J. Econ. Entomol.* **47**, 756–765 (1954).
248. Wohlgenuth, R. Über die Ei- und Larvalentwicklung von *Trogoderma angustum* Sol., (Dermestidae). *Anz. Schadlingskunde* **40**, 83–91 (1967).
249. Klein, D. R. Introduction increase and crash of reindeer on St. Matthew Island. *J. Wildl. Manag.* **32**, 350–367 (1968).
250. Petranka, J. W. The effects of severe winter weather on *Plethodon dorsalis* and *Plethodon richmondi* populations in central Kentucky. *J. Herpetol.* **13**, 369–371 (1979).
251. Smith, K. G. Drought-induced changes in avian community structure along a montane sere. *Ecology* **63**, 952–961 (1982).
252. McClure, M. S. Temperature and host availability affect the distribution of *Matsucoccus matsumurae* (Kuwana) (Homoptera, Margarodidae) in Asia and North America. *Ann. Entomol. Soc. Am.* **76**, 761–765 (1983).
253. Peckol, P. & Searles, R. B. Effects of seasonality and disturbance on population development in a Carolina continental-shelf community. *Bull. Mar. Sci.* **33**, 67–86 (1983).
254. Ridpath, M. G. & Brooker, M. G. The breeding of the wedge-tailed eagle *Aquila audax* in relation to its food supply in arid Western Australia. *Ibis* **128**, 177–194 (1986).
255. Shepherd, P., Crockett, T., De Santo, T. L. & Bildstein, K. L. The impact of hurricane Hugo on the breeding ecology of wading birds at Pumpkinseed Island, Hobcaw Barony, South Carolina. *Col. Waterbirds* **14**, 150–157 (1991).
256. Willig, M. R. & Camilo, G. R. The effect of hurricane Hugo on 6 invertebrate species in the Luquillo experimental forest of Puerto Rico. *Biotropica* **23**, 455–461 (1991).
257. Woolbright, L. L. The impact of hurricane Hugo on forest frogs in Puerto Rico. *Biotropica* **23**, 462–467 (1991).
258. Marone, L. Seasonal and year-to-year fluctuations of bird populations and guilds in the Monte Desert, Argentina (Fluctuaciones Estacionales e Interanuales de Poblaciones y Gremios de Aves en el Desierto del Monte, Argentina). *J. Field Ornithol.* **63**, 294–308 (1992).
259. Wauer, R. H. & Wunderle, J. M. The effect of hurricane Hugo on bird populations on St. Croix, U.S. Virgin Islands. *Wilson Bull.* **104**, 656–673 (1992).
260. Wunderle, J. M., Lodge, D. J. & Waide, R. B. Short-term effects of hurricane Gilbert on terrestrial bird populations on Jamaica. *Auk* **109**, 148–166 (1992).
261. Letourneur, Y., Harmelin-Vivien, M. & Galzin, R. Impact of hurricane Firinga on fish community structure on fringing reefs of Reunion Island, S.W. Indian Ocean. *Environ. Biol. Fish.* **37**, 109–120 (1993).
262. Wunderle, J. M. Responses of bird populations in a Puerto Rican forest to hurricane Hugo – the first 18 months. *Condor* **97**, 879–896 (1995).
263. Torres, A. R. & Leberg, P. L. Initial changes in habitat and abundance of cavity-nesting birds and the northern parula following hurricane Andrew. *Condor* **98**, 483–490 (1996).
264. Woolbright, L. L. Disturbance influences long-term population patterns in the Puerto Rican frog, *Eleutherodactylus coqui* (Anura: Leptodactylidae). *Biotropica* **28**, 493–501 (1996).
265. Strong, A. M., Bancroft, G. T. & Jewell, S. D. Hydrological constraints on tricolored heron and snowy egret resource use. *Condor* **99**, 894–905 (1997).
266. Letcher, B. H. & Terrick, T. D. Maturation of male age-0 Atlantic salmon following a massive, localized flood. *J. Fish. Biol.* **53**, 1243–1252 (1998).
267. Miller, A. C. & Payne, B. S. Effects of disturbances on large-river mussel assemblages. *Regul. Rivers Res. Manag.* **14**, 179–190 (1998).
268. Murphy, M. T., Kerri, L. C. & Karmel, L. M. Winter bird communities on San Salvador, Bahamas (Comunidades de Aves Invernales en San Salvador, Bahamas). *J. Field Ornithol.* **69**, 402–414 (1998).
269. Spiller, D. A., Losos, J. B. & Schoener, T. W. Impact of a catastrophic hurricane on island populations. *Science* **281**, 695–697 (1998).
270. Swilling, W. R., Wooten, M. C., Holler, N. R. & Lynn, W. J. Population dynamics of Alabama beach mice (*Peromyscus polionotus ammobates*) following hurricane Opal. *Am. Midl. Nat.* **140**, 287–298 (1998).
271. Orsi, M. L. & Agostinho, A. A. Fish species introduction by accidental escape from aquaculture in the high Parana River Basin. *Rev. Bras. Zool.* **16**, 557–560 (1999).
272. Steenhof, K., Kochert, M. N., Carpenter, L. B. & Lehman, R. N. Long-term prairie falcon population changes in relation to prey abundance, weather, land uses, and habitat conditions. *Condor* **101**, 28–41 (1999).
273. Verner, J. & Purcell, K. L. Fluctuating populations of house wrens and Bewick's wrens in foothills of the western Sierra Nevada of California. *Condor* **101**, 219–229 (1999).
274. Labbe, T. R. & Fausch, K. D. Dynamics of intermittent stream habitat regulate persistence of a threatened fish at multiple scales. *Ecol. Appl.* **10**, 1774–1791 (2000).
275. Reaser, J. K. Demographic analysis of the Columbia spotted frog (*Rana luteiventris*): case study in spatiotemporal variation. *Can. J. Zool.* **78**, 1158–1167 (2000).
276. Rodríguez-Durán, A. & Vázquez, R. The bat *Artibeus jamaicensis* in Puerto Rico (West Indies): seasonality of diet, activity, and effect of a hurricane. *Acta Chiropt.* **03**, 53–61 (2001).
277. Sommer, B., Sommer, B., Horwitz, P. & Horwitz, P. Water quality and macroinvertebrate response to acidification following intensified summer droughts in a Western Australian wetland. *Mar. Freshw. Res.* **52**, 1015–1021 (2001).
278. Soto, D., Jara, F. & Moreno, C. Escaped salmon in the inner seas, southern Chile: facing ecological and social conflicts. *Ecol. Appl.* **11**, 1750–1762 (2001).
279. Parchaso, F. & Thompson, J. K. Influence of hydrologic processes on reproduction of the introduced bivalve *Potamocorbula amurensis* in northern San Francisco Bay, California. *Pac. Sci.* **56**, 329–345 (2002).
280. Roghair, C. N., Dolloff, C. A. & Underwood, M. K. Response of a brook trout population and instream habitat to a catastrophic flood and debris flow. *Trans. Am. Fish. Soc.* **131**, 718–730 (2002).
281. Schlatter, R. P., Navarro, R. A. & Corti, P. Effects of El Niño Southern Oscillation on numbers of black-necked swans at Río Cruces Sanctuary, Chile. *Waterbirds* **25**, 114–122 (2002).
282. Short, J., Kinnear, J. E. & Robley, A. Surplus killing by introduced predators in Australia—evidence for ineffective anti-predator adaptations in native prey species? *Biol. Conserv.* **103**, 283–301 (2002).
283. Thorp, J. H., Alexander, J. E. & Cobbs, G. A. Coping with warmer, large rivers: a field experiment on potential range expansion of northern quagga mussels (*Dreissena bugensis*). *Freshw. Biol.* **47**, 1779–1790 (2002).
284. Lopez, R. R., Silvy, N. J., Labisky, R. F. & Frank, P. A. Hurricane impacts on key deer in the Florida Keys. *J. Wildl. Manag.* **67**, 280–288 (2003).
285. Natsumeda, T. Effects of a severe flood on the movements of Japanese fluvial sculpin. *Environ. Biol. Fish.* **68**, 417–424 (2003).
286. West, J. M., Williams, G. D., Madon, S. P. & Zedler, J. B. Integrating spatial and temporal variability into the analysis of fish food web linkages in Tijuana Estuary. *Environ. Biol. Fish.* **67**, 297–309 (2003).

287. Kohno, K., Soemori, H. & Takahashi, K. Seasonal occurrence of *Plutella xylostella* (Lepidoptera: Yponomeutidae) on Ishigaki-jima Island, with special reference to their sudden occurrence associated with a typhoon. *Appl. Entomol. Zool.* **39**, 119–125 (2004).
288. Masello, J. F. & Quillfeldt, P. Consequences of La Niña phase of ENSO for the survival and growth of nestling burrowing parrots on the Atlantic coast of South America. *Emu Austral Ornithol.* **104**, 337–346 (2004).
289. Schoener, T. W., Spiller, D. A. & Losos, J. B. Variable ecological effects of hurricanes: the importance of seasonal timing for survival of lizards on Bahamian islands. *Proc. Natl Acad. Sci. USA* **101**, 177–181 (2004).
290. Specziar, A. Life history pattern and feeding ecology of the introduced eastern mosquitofish, *Gambusia holbrooki*, in a thermal spa under temperate climate, of Lake Heviz, Hungary. *Hydrobiologia* **522**, 249–260 (2004).
291. Wunderle, J. M., Mercado, J. E., Parresol, B. & Terranova, E. Spatial ecology of Puerto Rican boas (*Epicrates inornatus*) in a hurricane impacted forest. *Biotropica* **36**, 555–571 (2004).
292. Steinhart, G. B., Leonard, N. J., Stein, R. A. & Marschall, E. A. Effects of storms, angling, and nest predation during angling on smallmouth bass (*Micropterus dolomieu*) nest success. *Can. J. Fish. Aquat. Sci.* **62**, 2649–2660 (2005).
293. Tejeda-Cruz, C. & Sutherland, W. J. Cloud forest bird responses to unusually severe storm damage. *Biotropica* **37**, 88–95 (2005).
294. Vilella, F. J. & Fogarty, J. H. Diversity and abundance of forest frogs (Anura: Leptodactylidae) before and after hurricane Georges in the Cordillera Central of Puerto Rico. *Caribb. J. Sci.* **41**, 157–162 (2005).
295. White, T. H., Collazo, J. A., Vilella, F. J. & Guerrer, S. A. Effects of hurricane Georges on habitat use by captive-reared Hispaniolan parrots (*Amazona ventralis*) released in the Dominican Republic. *Ornitol. Neotrop.* **16**, 405–417 (2005).
296. Margaritora, F. G. et al. Recent trophic changes in Lake Pusiano (northern Italy) with particular reference to the influence of hydrodynamics on the zooplankton community. *Chem. Ecol.* **22**, 37–47 (2006).
297. Mouthon, J. & Daufresne, M. Effects of the 2003 heatwave and climatic warming on mollusc communities of the Saone: a large lowland river and of its two main tributaries (France). *Glob. Change Biol.* **12**, 441–449 (2006).
298. Moynahan, B. J., Lindberg, M. S. & Thomas, J. W. Factors contributing to process variance in annual survival of female greater sage grouse in Montana. *Ecol. Appl.* **16**, 1529–1538 (2006).
299. Paperno, R. et al. The disruption and recovery of fish communities in the Indian River Lagoon, Florida, following two hurricanes in 2004. *Estuaries Coasts* **29**, 1004–1010 (2006).
300. Pusey, B., Burrows, D., Arthington, A. & Kennard, M. Translocation and spread of piscivorous fishes in the Burdekin River, north-eastern Australia. *Biol. Invasions* **8**, 965–977 (2006).
301. Rius, M. & McQuaid, C. D. Wave action and competitive interaction between the invasive mussel *Mytilus galloprovincialis* and the indigenous *Perna perna* in South Africa. *Mar. Biol.* **150**, 69–78 (2006).
302. Ruiz-Campos, G. et al. Distribution and abundance of the endangered killifish *Fundulus lima*, and its interaction with exotic fishes in oases of central Baja California, Mexico. *Southwest. Nat.* **51**, 502–509 (2006).
303. Santos, M., Brites, D. & Laayouni, H. Thermal evolution of pre-adult life history traits, geometric size and shape, and developmental stability in *Drosophila subobscura*. *J. Evol. Biol.* **19**, 2006–2021 (2006).
304. Scorolli, A. L., Lopez Cazorra, A. C. & Tejera, L. A. Unusual mass mortality of feral horses during a violent rainstorm in Parque Provincial Tornquist, Argentina. *Mastozool. Neotrop.* **13**, 255–258 (2006).
305. Stevens, P. W., Blewett, D. A. & Casey, J. P. Short-term effects of a low dissolved oxygen event on estuarine fish assemblages following the passage of hurricane Charley. *Estuaries Coasts* **29**, 997–1003 (2006).
306. Storms, D. et al. Influence of hurricane Lothar on red and roe deer winter diets in the Northern Vosges, France. *Ecol. Manag.* **237**, 164–169 (2006).
307. Switzer, T. S., Winner, B. L., Dunham, N. M., Whittington, J. A. & Thomas, M. Influence of sequential hurricanes on nekton communities in a southeast Florida estuary: short-term effects in the context of historical variations in freshwater inflow. *Estuaries Coasts* **29**, 1011–1018 (2006).
308. Tossas, A. G. Effects of hurricane Georges on the resident avifauna of Maricao State Forest, Puerto Rico. *Caribb. J. Sci.* **42**, 81–87 (2006).
309. Wilson, J. & Peach, W. Impact of an exceptional winter flood on the population dynamics of bearded tits (*Panurus biarmicus*). *Anim. Conserv.* **9**, 463–473 (2006).
310. Yackel Adams, A. A., Skagen, S. K. & Savidge, J. A. Modeling post-fledging survival of lark buntings in response to ecological and biological factors. *Ecology* **87**, 178–188 (2006).
311. Robertson, H. A. & Saul, E. K. *Conservation of Kakerori (Pomarea dimidiata) in the Cook Islands in 2005/06* DOC Research and Development Series 285 (New Zealand Department of Conservation, 2007).
312. Robinson, R. A., Baillie, S. R. & Crick, H. Q. P. Weather-dependent survival: implications of climate change for passerine population processes. *Ibis* **149**, 357–364 (2007).
313. Sangiorgio, F., Fonnesu, A. & Mancinelli, G. Effect of drought frequency and other reach characteristics on invertebrate communities and litter breakdown in the intermittent Mediterranean river Pula (Sardinia, Italy). *Int. Rev. Hydrobiol.* **92**, 156–172 (2007).
314. Spiller, D. A. & Schoener, T. W. Alteration of island food-web dynamics following major disturbance by hurricanes. *Ecology* **88**, 37–41 (2007).
315. Urban, M. C., Phillips, B. L., Skelly, D. K. & Shine, R. The cane toad's (*Chaunus [Bufo] marinus*) increasing ability to invade Australia is revealed by a dynamically updated range model. *Proc. R. Soc. B* **274**, 1413–1419 (2007).
316. Ward, N. L. & Masters, G. J. Linking climate change and species invasion: an illustration using insect herbivores. *Glob. Change Biol.* **13**, 1605–1615 (2007).
317. Watts, B. D. & Byrd, M. A. Impact of hurricane Isabel on bald eagle nests and reproductive performance in the lower Chesapeake Bay. *Condor* **109**, 206–209 (2007).
318. Winne, C. T., Willson, J. D., Todd, B. D., Andrews, K. M. & Gibbons, J. W. Enigmatic decline of a protected population of eastern kingsnakes, *Lampropeltis getula*, in South Carolina. *Copeia* **2007**, 507–519 (2007).
319. Kanowski, J., Winter, J. W. & Catterall, C. P. Impacts of cyclone Larry on arboreal folivorous marsupials endemic to upland rainforests of the Atherton Tableland, Australia. *Austral Ecol.* **33**, 541–548 (2008).
320. Lee, Y.-F. et al. Spatiotemporal variation in avian diversity and the short-term effects of typhoons in tropical reef-karst forests on Taiwan. *Zool. Sci.* **25**, 593–603 (2008).
321. McAllan, B. M., Westman, W., Crowther, M. S. & Dickman, C. R. Morphology, growth and reproduction in the Australian house mouse: differential effects of moderate temperatures. *Biol. J. Linn. Soc.* **94**, 21–30 (2008).
322. Poirrier, M. A., del Rey, Z. R. & Spalding, E. A. Acute disturbance of lake Pontchartrain benthic communities by hurricane Katrina. *Estuaries Coasts* **31**, 1221–1228 (2008).

323. Powlesland, R. G., Butler, D. J. & Westbrooke, I. M. Was tropical cyclone Heta or hunting by people responsible for decline of the lupe (*Ducula pacifica*) (Aves: Columbidae) population on Niue during 1994–2004? *Pac. Sci.* **62**, 461–471 (2008).
324. Preisser, E. L., Elkinton, J. S. & Abell, K. Evolution of increased cold tolerance during range expansion of the elongate hemlock scale *Fiorinia externa* Ferris (Hemiptera: Diaspididae). *Ecol. Entomol.* **33**, 709–715 (2008).
325. Schneider, K. R. Heat stress in the intertidal: comparing survival and growth of an invasive and native mussel under a variety of thermal conditions. *Biol. Bull.* **215**, 253–264 (2008).
326. Tjorve, K. M. C. & Underhill, L. G. Breeding phenology of African black oystercatchers *Haematopus moquini* on Robben Island, South Africa. *Ostrich* **79**, 141–146 (2008).
327. Tossas, A. G. Reproductive success of the Puerto Rican vireo in a montane habitat. *Wilson J. Ornithol.* **120**, 460–466 (2008).
328. Wakeford, M., Done, T. J. & Johnson, C. R. Decadal trends in a coral community and evidence of changed disturbance regime. *Coral Reefs* **27**, 1–13 (2008).
329. Yaukey, P. H. Effects of hurricane Katrina on the urban resident landbirds of New Orleans, Louisiana. *Condor* **110**, 158–161 (2008).
330. Lopez-Lopez, E., Sedeno-Diaz, J. E., Vega, P. T. & Oliveros, E. Invasive mollusks *Tarebia granifera* Lamarck, 1822 and *Corbicula fluminea* Mueller, 1774 in the Tuxpam and Tecolutla rivers, Mexico: spatial and seasonal distribution patterns. *Aquat. Invasions* **4**, 435–450 (2009).
331. Neveu, A. Incidence of climate on common frog breeding: long-term and short-term changes. *Acta Oecol* **35**, 671–678 (2009).
332. Piazza, B. P. & La Peyre, M. K. The effect of hurricane Katrina on nekton communities in the tidal freshwater marshes of Breton Sound, Louisiana, USA. *Estuar. Coast. Shelf Sci.* **83**, 97–104 (2009).
333. Piessens, K., Adriaens, D., Jacquemyn, H. & Honnay, O. Synergistic effects of an extreme weather event and habitat fragmentation on a specialised insect herbivore. *Oecologia* **159**, 117–126 (2009).
334. Powell, B. E., Brighwell, R. J. & Silverman, J. Effect of an invasive and native ant on a field population of the black citrus aphid (Hemiptera: Aphididae). *Environ. Entomol.* **38**, 1618–1625 (2009).
335. Pries, A. J., Branch, L. C. & Miller, D. L. Impact of hurricanes on habitat occupancy and spatial distribution of beach mice. *J. Mammal.* **90**, 841–850 (2009).
336. Schriever, T. A., Ramspott, J., Crother, B. I. & Fontenot, C. L. Effects of hurricanes Ivan, Katrina, and Rita on a southeastern Louisiana herpetofauna. *Wetlands* **29**, 112–122 (2009).
337. Kawabata, Y. et al. Effects of a tropical cyclone on the distribution of hatchery-reared black-spot tuskfish *Choerodon schoenleinii* determined by acoustic telemetry. *J. Fish. Biol.* **77**, 627–642 (2010).
338. Kroon, F. J. & Ludwig, J. A. Response and recovery of fish and invertebrate assemblages following flooding in five tributaries of a sub-tropical river. *Mar. Freshw. Res.* **61**, 86–96 (2010).
339. Leberfinger, K., Bohman, I. & Herrmann, J. Drought impact on stream detritivores: experimental effects on leaf litter breakdown and life cycles. *Hydrobiologia* **652**, 247–254 (2010).
340. Luja, V. H. & Rodriguez-Estrella, R. Are tropical cyclones sources of natural selection? Observations on the abundance and behavior of frogs affected by extreme climatic events in the Baja California Peninsula, Mexico. *J. Arid Environ.* **74**, 1345–1347 (2010).
341. Martin, A. P. The conservation genetics of Ash Meadows pupfish populations. I. The warm springs pupfish *Cyprinodon nevadensis pectoralis*. *Conserv. Genet.* **11**, 1847–1857 (2010).
342. McGlenn, D. J., Churchwell, R. T. & Palmer, M. W. Effects of a tornado on birds in a cross timbers community. *Southwest. Nat.* **55**, 460–466 (2010).
343. Miranda, N. A. F., Perissinotto, R. & Appleton, C. C. Salinity and temperature tolerance of the invasive freshwater gastropod *Tarebia granifera*. *S. Afr. J. Sci.* **106**, 55–61 (2010).
344. Rittenhouse, C. D. et al. Avifauna response to hurricanes: regional changes in community similarity. *Glob. Change Biol.* **16**, 905–917 (2010).
345. Rousseau, Y., Galzin, R. & Maréchal, J.-P. Impact of hurricane Dean on coral reef benthic and fish structure of Martinique, French West Indies. *Cybium* **34**, 243–256 (2010).
346. Stevens, P. W., Blewett, D. A., Champeau, T. R. & Stafford, C. J. Posthurricane recovery of riverine fauna reflected in the diet of an apex predator. *Estuaries Coasts* **33**, 59–66 (2010).
347. Stone, A. C., Gehring, C. A. & Whitham, T. G. Drought negatively affects communities on a foundation tree: growth rings predict diversity. *Oecologia* **164**, 751–761 (2010).
348. Zhang, F.-P., Zhong, J.-H., Jiang, B.-F., Li, S.-W. & Miao, F.-Q. Thermal tolerance in the pine armored scale, *Hemiberlesia pitysoiphila* Takagi (Homoptera: Diaspididae), along an altitudinal gradient. *Acta Entomol. Sin.* **53**, 68–75 (2010).
349. Kano, Y. et al. Fluctuation and variation in stream-fish assemblages after a catastrophic flood in the Miyagawa River, Japan. *Environ. Biol. Fish.* **92**, 447–460 (2011).
350. Kerezy, A., Balcombe, S. R., Arthington, A. H. & Bunn, S. E. Continuous recruitment underpins fish persistence in the arid rivers of far-western Queensland, Australia. *Mar. Freshw. Res.* **62**, 1178–1190 (2011).
351. Leuven, R. S. E. W. et al. Differences in sensitivity of native and exotic fish species to changes in river temperature. *Curr. Zool.* **57**, 852–862 (2011).
352. Lewis, M. A., Goodman, L. R., Chancy, C. A. & Jordan, S. J. Fish assemblages in three northwest Florida urbanized bayous before and after two hurricanes. *J. Coast. Res.* **27**, 35–45 (2011).
353. Lorenz, O. T. & O’Connell, M. T. Establishment and post-hurricane survival of the non-native Rio Grande cichlid (*Herichthys cyanoguttatus*) in the Greater New Orleans Metropolitan Area. *Southeast. Nat.* **10**, 673–686 (2011).
354. Lue, Z.-C. & Wan, F.-H. Using double-stranded RNA to explore the role of heat shock protein genes in heat tolerance in *Bemisia tabaci* (Gennadius). *J. Exp. Biol.* **214**, 764–769 (2011).
355. Maazouzi, C., Piscart, C., Legier, F. & Hervant, F. Ecophysiological responses to temperature of the ‘killer shrimp’ *Dikerogammarus villosus*: is the invader really stronger than the native *Gammarus pulex*? *Comp. Biochem. Physiol. A* **159**, 268–274 (2011).
356. Oliveira, M. D., Calheiros, D. F., Jacobi, C. M. & Hamilton, S. K. Abiotic factors controlling the establishment and abundance of the invasive golden mussel *Limnoperna fortunei*. *Biol. Invasions* **13**, 717–729 (2011).
357. Pujolar, J. M. et al. The effect of recurrent floods on genetic composition of marble trout populations. *PLoS ONE* **6**, e23822 (2011).
358. Schlieff, J. & Mutz, M. Leaf decay processes during and after a supra-seasonal hydrological drought in a temperate lowland stream. *Int. Rev. Hydrobiol.* **96**, 633–655 (2011).
359. Soster, F. M., McCall, P. L. & Herrmann, K. A. Decadal changes in the benthic invertebrate community in western Lake Erie between 1981 and 2004. *J. Gt. Lakes Res.* **37**, 226–237 (2011).
360. Yoon, J.-D., Jang, M.-H. & Joo, G.-J. Effect of flooding on fish assemblages in small streams in South Korea. *Limnology* **12**, 197–203 (2011).
361. Zhou, Z.-S., Guo, J.-Y., Michaud, J. P., Li, M. & Wan, F.-H. Variation in cold hardiness among geographic populations of the ragweed beetle, *Ophraella communa* LeSage (Coleoptera: Chrysomelidae), a biological control agent of *Ambrosia artemisiifolia* L. (Asterales: Asteraceae), in China. *Biol. Invasions* **13**, 659–667 (2011).

362. Kiernan, J. D. & Moyle, P. B. Flows, droughts, and aliens: factors affecting the fish assemblage in a Sierra Nevada, California, stream. *Ecol. Appl.* **22**, 1146–1161 (2012).
363. Ramírez-Barajas, P. J., Islebe, G. A. & Calmé, S. Impact of hurricane Dean (2007) on game species of the Selva Maya, Mexico. *Biotropica* **44**, 402–411 (2012).
364. Ramniwas, S., Kajla, B. & Parkash, R. Extreme physiological tolerance leads the wide distribution of *Zaprionus indianus* (Diptera: Drosophilidae) in temperate world. *Acta Entomol. Sin.* **55**, 1295–1305 (2012).
365. Reichert, B. E., Cattau, C. E., Fletcher, R. J. Jr., Kendall, W. L. & Kitchens, W. M. Extreme weather and experience influence reproduction in an endangered bird. *Ecology* **93**, 2580–2589 (2012).
366. Sherley, R. B., Ludynia, K., Underhill, L. G., Jones, R. & Kemper, J. Storms and heat limit the nest success of bank cormorants: implications of future climate change for a surface-nesting seabird in southern Africa. *J. Ornithol.* **153**, 441–455 (2012).
367. Sobek-Swant, S., Crosthwaite, J. C., Lyons, D. B. & Sinclair, B. J. Could phenotypic plasticity limit an invasive species? Incomplete reversibility of mid-winter deacclimation in emerald ash borer. *Biol. Invasions* **14**, 115–125 (2012).
368. Sorribas, J., van Baaren, J. & Garcia-Mari, F. Effects of climate on the introduction, distribution and biotic potential of parasitoids: applications to biological control of California red scale. *Biol. Control* **62**, 103–112 (2012).
369. Strand, A. et al. Impact of an icy winter on the Pacific oyster (*Crassostrea gigas* Thunberg, 1793) populations in Scandinavia. *Aquat. Invasions* **7**, 433–440 (2012).
370. Thomas, S. M., Obermayr, U., Fischer, D., Kreyling, J. & Beierkuhnlein, C. Low-temperature threshold for egg survival of a post-diapause and non-diapause European aedine strain, *Aedes albopictus* (Diptera: Culicidae). *Parasit. Vectors* **5**, 100 (2012).
371. Verbrugge, L. N. H., Schipper, A. M., Huijbregts, M. A. J., Van der Velde, G. & Leuven, R. S. E. W. Sensitivity of native and non-native mollusc species to changing river water temperature and salinity. *Biol. Invasions* **14**, 1187–1199 (2012).
372. Weir, S. M. & Salice, C. J. High tolerance to abiotic stressors and invasion success of the slow-growing freshwater snail, *Melanooides tuberculatus*. *Biol. Invasions* **14**, 385–394 (2012).
373. Yao, C.-L. & Somero, G. N. The impact of acute temperature stress on hemocytes of invasive and native mussels (*Mytilus galloprovincialis* and *Mytilus californianus*): DNA damage, membrane integrity, apoptosis and signaling pathways. *J. Exp. Biol.* **215**, 4267–4277 (2012).
374. Yaukey, P. H. Population changes of urban land birds in the three years following the hurricane Katrina flood. *Nat. Hazards* **61**, 1203–1217 (2012).
375. Kats, L. B. et al. Effects of natural flooding and manual trapping on the facilitation of invasive crayfish–native amphibian coexistence in a semi-arid perennial stream. *J. Arid Environ.* **98**, 109–112 (2013).
376. Kerezszy, A., Balcombe, S. R., Tischler, M. & Arthington, A. H. Fish movement strategies in an ephemeral river in the Simpson Desert, Australia. *Austral Ecol.* **38**, 798–808 (2013).
377. Ledger, M. E. et al. in *Advances in Ecological Research* Vol. 48 (eds Guy Woodward, G. & O’Gorman, E. J.) 343–395 (Academic Press, 2013).
378. Lindsay, A. R. & Haas, S. C. G. DNA from feces and museum specimens confirms a first state record bird. *Occas. Pap. Mus. Zool. Univ. Mich.* **742**, 1–10 (2013).
379. Martinez, J. E., Jimenez-Franco, M. V., Zuberogoitia, I., Leon-Ortega, M. & Calvo, J. F. Assessing the short-term effects of an extreme storm on Mediterranean forest raptors. *Acta Oecol.* **48**, 47–53 (2013).
380. Milner, A. M., Robertson, A. L., McDermott, M. J., Klaar, M. J. & Brown, L. E. Major flood disturbance alters river ecosystem evolution. *Nat. Clim. Change* **3**, 137–141 (2013).
381. Moreno-Valcarcel, R., Oliva-Paterna, F. J., Arribas, C. & Fernandez-Delgado, C. Fish composition and assemblage in the anthropogenic-modified tidally-restricted Donana (Spain) marshlands. *Estuar. Coast. Shelf Sci.* **119**, 54–63 (2013).
382. Morgan, E., O’ Riordan, R. M. & Culloty, S. C. Climate change impacts on potential recruitment in an ecosystem engineer. *Ecol. Evol.* **3**, 581–594 (2013).
383. Munroe, D. et al. Oyster mortality in Delaware Bay: impacts and recovery from hurricane Irene and tropical storm Lee. *Estuar. Coast. Shelf Sci.* **135**, 209–219 (2013).
384. Parker, M. L., Arnold, W. S., Geiger, S. P., Gorman, P. & Leone, E. H. Impacts of freshwater management activities on eastern oyster (*Crassostrea virginica*) density and recruitment: recovery and long-term stability in seven Florida estuaries. *J. Shellfish Res.* **32**, 695–708 (2013).
385. Raynor, E. J., Pierce, A. R., Owen, T. M., Leumas, C. M. & Rohwer, F. C. Short-term demographic responses of a coastal waterbird community after two major hurricanes. *Waterbirds* **36**, 88–93 (2013).
386. Rongo, T. & van Woesik, R. The effects of natural disturbances, reef state, and herbivorous fish densities on ciguatera poisoning in Rarotonga, southern Cook Islands. *Toxicon* **64**, 87–95 (2013).
387. Schoeman, C. S. & Samways, M. J. Temporal shifts in interactions between alien trees and the alien Argentine ant on native ants. *J. Insect Conserv.* **17**, 911–919 (2013).
388. Sentis, A., Hemptinne, J.-L. & Brodeur, J. Effects of simulated heat waves on an experimental plant-herbivore-predator food chain. *Glob. Change Biol.* **19**, 833–842 (2013).
389. Navarro, F. K. S. P., de Souza Rezende, R. & Goncalves Junior, J. F. Experimental assessment of temperature increase and presence of predator carcass changing the response of invertebrate shredders. *Biota Neotrop.* **13**, 28–33 (2013).
390. Smith, W. H. Amphibians and large, infrequent forest disturbances: an extreme wind event facilitates habitat creation and anuran breeding. *Herpetol. Conserv. Biol.* **8**, 732–740 (2013).
391. Spinuzzi, S., Schneider, K. R., Walters, L. J., Yuan, W. S. & Hoffman, E. A. Tracking the distribution of non-native marine invertebrates (*Mytella charruana*, *Perna viridis* and *Megabalanus coccopoma*) along the south-eastern USA. *Mar. Biodivers. Rec.* **6**, e55 (2013).
392. Sustek, Z. Carabid communities (Coleoptera: Carabidae) in spruce forests in Central Europe. *Olten. Stud. Comun. Stiint. Nat.* **29**, 140–154 (2013).
393. Walter, S. T., Carlross, M. R., Hess, T. J. & Leberg, P. L. Hurricane, habitat degradation, and land loss effects on brown pelican nesting colonies. *J. Coast. Res.* **29**, 187–195 (2013).
394. Wu, L.-H., Wang, C.-P. & Wu, W.-J. Effects of temperature and adult nutrition on the development of *Acanthoscelides macropthalmus*, a natural enemy of an invasive tree, *Leucaena leucocephala*. *Biol. Control* **65**, 322–329 (2013).
395. Yu, J., Tang, D., Li, Y., Huang, Z. & Chen, G. Increase in fish abundance during two typhoons in the South China Sea. *Adv. Space Res.* **51**, 1734–1749 (2013).
396. Zahorska, E., Balazova, M. & Surova, M. Morphology, sexual dimorphism and size at maturation in topmouth gudgeon (*Pseudorasbora parva*) from the heated Lake Lichenskie (Poland). *Knowl. Manage. Aquat. Ecosyst.* <https://doi.org/10.1051/kmae/2013074> (2013).
397. Kerezszy, A., Arthington, A. H. & Balcombe, S. R. Fish distribution in far western Queensland, Australia: the importance of habitat, connectivity and natural flows. *Diversity* **6**, 380–395 (2014).
398. Lofgren, S., Grandin, U. & Stendera, S. Long-term effects on nitrogen and benthic fauna of extreme weather events: examples from two Swedish headwater streams. *Ambio* **43**, 58–76 (2014).

399. Narayan, E. J. & Hero, J.-M. Acute thermal stressor increases glucocorticoid response but minimizes testosterone and locomotor performance in the cane toad (*Rhinella marina*). *PLoS ONE* <https://doi.org/10.1371/journal.pone.0092090> (2014).
400. Peacock, D., Wakelin-King, G. A. & Shepherd, B. Cane toads (*Rhinella marina*) in south-western Queensland: invasion front, spread and how Cooper Creek geomorphology could enable invasion into north-eastern South Australia. *Aust. J. Zool.* **62**, 366–373 (2014).
401. Richards, D. R., Maltby, L., Moggridge, H. L. & Warren, P. H. European water voles in a reconnected lowland river floodplain: habitat preferences and distribution patterns following the restoration of flooding. *Wetl. Ecol. Manag.* **22**, 539–549 (2014).
402. Zahorska, E., Kovac, V., Svolikova, K. & Kapusta, A. Reproductive parameters of topmouth gudgeon (*Pseudorasbora parva*) from a heated Lake Lichenskie (Poland). *Cent. Eur. J. Biol.* **9**, 212–219 (2014).
403. Kitanishi, S. & Yamamoto, T. The effects of severe flooding on native masu salmon and nonnative rainbow trout in the Atsuta River, Hokkaido, Japan. *J. Freshw. Ecol.* **30**, 589–596 (2015).
404. Novais, A., Souza, A. T., Ilarri, M., Pascoal, C. & Sousa, R. From water to land: how an invasive clam may function as a resource pulse to terrestrial invertebrates. *Sci. Total Environ.* **538**, 664–671 (2015).
405. Piggott, J. J., Townsend, C. R. & Matthaei, C. D. Climate warming and agricultural stressors interact to determine stream macroinvertebrate community dynamics. *Glob. Change Biol.* **21**, 1887–1906 (2015).
406. Selwood, K. E. et al. A bust but no boom: responses of floodplain bird assemblages during and after prolonged drought. *J. Anim. Ecol.* **84**, 1700–1710 (2015).
407. Senner, N. R. et al. When Siberia came to the Netherlands: the response of continental black-tailed godwits to a rare spring weather event. *J. Anim. Ecol.* **84**, 1164–1176 (2015).
408. Stubbington, R., Boulton, A. J., Little, S. & Wood, P. J. Changes in invertebrate assemblage composition in benthic and hyporheic zones during a severe suprasedasonal drought. *Freshw. Sci.* **34**, 344–354 (2015).
409. Tinsley, R. C., Stott, L. C., Viney, M. E., Mable, B. K. & Tinsley, M. C. Extinction of an introduced warm-climate alien species, *Xenopus laevis*, by extreme weather events. *Biol. Invasions* **17**, 3183–3195 (2015).
410. Vallieres, R., Rochefort, S., Berthiaume, R., Hebert, C. & Bause, E. Effect of simulated fall heat waves on cold hardiness and winter survival of hemlock looper, *Lambdina fiscellaria* (Lepidoptera: Geometridae). *J. Insect Physiol.* **73**, 60–69 (2015).
411. Woodward, G., Bonada, N., Feeley, H. B. & Giller, P. S. Resilience of a stream community to extreme climatic events and long-term recovery from a catastrophic flood. *Freshw. Biol.* **60**, 2497–2510 (2015).
412. Kangur, K. et al. Changes in water temperature and chemistry preceding a massive kill of bottom-dwelling fish: an analysis of high-frequency buoy data of shallow Lake Vortsjarv (Estonia). *Inland Waters* **6**, 535–542 (2016).
413. Karahan, A., Douek, J., Paz, G. & Rinkevich, B. Population genetics features for persistent, but transient, *Botryllus schlosseri* (Urochordata) congregations in a central Californian marina. *Mol. Phylogenet. Evol.* **101**, 19–31 (2016).
414. Klockmann, M., Schroeder, U., Karajoli, F. & Fischer, K. Simulating effects of climate change under direct and diapause development in a butterfly. *Entomol. Exp. Appl.* **158**, 60–68 (2016).
415. Mazzotti, F. J. et al. Large reptiles and cold temperatures: do extreme cold spells set distributional limits for tropical reptiles in Florida? *Ecosphere* **7**, e01439 (2016).
416. Olabarriall, C. et al. Response of two mytilids to a heatwave: the complex interplay of physiology, behaviour and ecological interactions. *PLoS ONE* <https://doi.org/10.1371/journal.pone.0164330> (2016).
417. Schulte, S. A. & Simons, T. R. Hurricane disturbance benefits nesting American oystercatchers (*Haematopus palliatus*). *Waterbirds* **39**, 327–337 (2016).
418. Su, N.-Y., Guidry, E., Mullins, A. J. & Cotonne, C. Reinvasion dynamics of subterranean termites (Isoptera: Rhinotermitidae) following the elimination of all detectable colonies in a large area. *J. Econ. Entomol.* **109**, 809–814 (2016).
419. Vander Vorste, R., Malard, F. & Datry, T. Is drift the primary process promoting the resilience of river invertebrate communities? A manipulative field experiment in an intermittent alluvial river. *Freshw. Biol.* **61**, 1276–1292 (2016).
420. Vander Vorste, R., Corti, R., Sagouis, A. & Datry, T. Invertebrate communities in gravel-bed, braided rivers are highly resilient to flow intermittence. *Freshw. Sci.* **35**, 164–177 (2016).
421. Wang, X. et al. Greater impacts from an extreme cold spell on tropical than temperate butterflies in southern China. *Ecosphere* **7**, e01315 (2016).
422. Wiman, N. G. et al. *Drosophila suzukii* population response to environment and management strategies. *J. Pest Sci.* **89**, 653–665 (2016).
423. Klockmann, M., Guenter, F. & Fischer, K. Heat resistance throughout ontogeny: body size constrains thermal tolerance. *Glob. Change Biol.* **23**, 686–696 (2017).
424. Kosmala, G., Christian, K., Brown, G. & Shine, R. Locomotor performance of cane toads differs between native-range and invasive populations. *R. Soc. Open Sci.* <https://doi.org/10.1098/rsos.170517> (2017).
425. Leicht, K., Seppala, K. & Seppala, O. Potential for adaptation to climate change: family-level variation in fitness-related traits and their responses to heat waves in a snail population. *BMC Evol. Biol.* **17**, 140 (2017).
426. Li, J. et al. Growth, longevity, and climate–growth relationships of *Corbicula fluminea* (Muller, 1774) in Hongze Lake, China. *Freshw. Sci.* **36**, 595–608 (2017).
427. Lu, Z. et al. Differences in the high-temperature tolerance of *Aphis craccivora* (Hemiptera: Aphididae) on cotton and soybean: implications for ecological niche switching among hosts. *Appl. Entomol. Zool.* **52**, 9–18 (2017).
428. Mayes, K. B., Wilde, G. R., McGarrity, M. E., Wolaver, B. D. & Caldwell, T. G. Watershed-scale conservation of native fishes in the Brazos River Basin, Texas. *Am. Fish. S. S.* **91**, 315–343 (2019).
429. McDowell, W. G., McDowell, W. H. & Byers, J. E. Mass mortality of a dominant invasive species in response to an extreme climate event: implications for ecosystem function. *Limnol. Oceanogr.* **62**, 177–188 (2017).
430. Nelson, D. et al. Experimental whole-stream warming alters community size structure. *Glob. Change Biol.* **23**, 2618–2628 (2017).
431. Nuhfer, A. J., Zorn, T. G. & Wills, T. C. Effects of reduced summer flows on the brook trout population and temperatures of a groundwater-influenced stream. *Ecol. Freshw. Fish.* **26**, 108–119 (2017).
432. O'Donnell, K. & Groden, E. Variation in captures of adult winter moths (*Operophtera brumata*) in coastal Maine over two years. *Northeast. Nat.* **24**, B72–B80 (2017).
433. Raine, A. F., Holmes, N. D., Travers, M., Cooper, B. A. & Day, R. H. Declining population trends of Hawaiian petrel and Newell's shearwater on the island of Kauai, Hawaii, USA. *Condor* **119**, 405–415 (2017).
434. Rusk, B. L. Long-term population monitoring of the critically endangered Grenada dove (*Leptotila wellsii*) on Grenada, West Indies. *J. Caribb. Ornithol.* **30**, 49–56 (2017).

435. Schoener, T. W., Kolbe, J. J., Leal, M., Losos, J. B. & Spiller, D. A. A multigenerational field experiment on eco-evolutionary dynamics of the influential lizard *Anolis sagrei*: a mid-term report. *Copeia* **105**, 543–549 (2017).
436. Wade, R. N., Karley, A. J., Johnson, S. N. & Hartley, S. E. Impact of predicted precipitation scenarios on multitrophic interactions. *Funct. Ecol.* **31**, 1647–1658 (2017).
437. Kenworthy, J. M., Davoult, D. & Lejeune, C. Compared stress tolerance to short-term exposure in native and invasive tunicates from the NE Atlantic: when the invader performs better. *Mar. Biol.* **165**, 164 (2018).
438. Lynch, D. T., Leasure, D. R. & Magoulick, D. D. The influence of drought on flow ecology relationships in Ozark Highland streams. *Freshw. Biol.* **63**, 946–968 (2018).
439. Mason-Romo, E. D. et al. Long-term population dynamics of small mammals in tropical dry forests, effects of unusual climate events, and implications for management and conservation. *Ecol. Manag.* **426**, 123–133 (2018).
440. Mutamiswa, R., Chidawanyika, F. & Nyamukondiwa, C. Superior basal and plastic thermal responses to environmental heterogeneity in invasive exotic stemborer *Chilo partellus* Swinhoe over indigenous *Busseola fusca* (Fuller) and *Sesamia calamistis* Hampson. *Physiol. Entomol.* **43**, 108–119 (2018).
441. Rachalewski, M., Kobak, J., Szczerkowska-Majchrzak, E. & Bacela-Spychalska, K. Some like it hot: factors impacting thermal preferences of two Ponto-Caspian amphipods *Dikerogammarus villosus* (Sovinsky, 1894) and *Dikerogammarus haemobaphes* (Eichwald, 1841). *PeerJ* <https://doi.org/10.7717/peerj.4871> (2018).
442. Ramirez, A. et al. Drought facilitates species invasions in an urban stream: results from a long-term study of tropical island fish assemblage structure. *Front. Ecol. Evol.* <https://doi.org/10.3389/fevo.2018.00115> (2018).
443. Verberk, W. C. E. P., Leuven, R. S. E. W., van der Velde, G. & Gabel, F. Thermal limits in native and alien freshwater peracarid Crustacea: the role of habitat use and oxygen limitation. *Funct. Ecol.* **32**, 926–936 (2018).
444. Kantola, T. et al. Hemlock woolly adelgid niche models from the invasive eastern North American range with projections to native ranges and future climates. *IForest* **12**, 149–159 (2019).
445. Landeira-Dabarca, A., Perez, J., Graca, M. A. S. & Boyero, L. Joint effects of temperature and litter quality on detritivore-mediated breakdown in streams. *Aquat. Sci.* **81**, 1 (2019).
446. Maiztegui, T., Baigun, C. R. M., Garcia de Souza, J. R., Weyl, O. L. F. & Colautti, D. C. Population responses of common carp *Cyprinus carpio* to floods and droughts in the Pampean wetlands of South America. *Neobiota* **48**, 25–44 (2019).
447. McDowell, W. G. & Sousa, R. Mass mortality events of invasive freshwater bivalves: current understanding and potential directions for future research. *Front. Ecol. Evol.* <https://doi.org/10.3389/fevo.2019.00331> (2019).
448. Morey, A. C., Venette, R. C. & Hutchison, W. D. Sublethal effects of subzero temperatures on the light brown apple moth, *Epiphyas postvittana*: fitness costs in response to partial freezing. *Insect Sci.* **26**, 311–321 (2019).
449. Negishi, J. N. et al. High resilience of aquatic community to a 100-year flood in a gravel-bed river. *Landsc. Ecol. Eng.* **15**, 143–154 (2019).
450. Perkin, J. S. et al. Extreme drought causes fish recruitment failure in a fragmented Great Plains riverscape. *Ecohydrology* **12**, e2120 (2019).
451. Puterka, G. J. et al. Distribution of a new invasive species, *Sipha maydis* (Heteroptera: Aphididae), on cereals and wild grasses in the Southern Plains and Rocky Mountain States. *J. Econ. Entomol.* **112**, 1713–1721 (2019).
452. Sanchez-Ramos, I., Gomez-Casado, E., Fernandez, C. E. & Gonzalez-Nunez, M. Reproductive potential and population increase of *Drosophila suzukii* at constant temperatures. *Entomol. Gen.* **39**, 103–115 (2019).
453. Toland, A. A., Wantuch, H. A., Mullins, D. E., Kuhar, T. P. & Salom, S. M. Seasonal assessment of supercooling points for two introduced and one native *Laricobius* spp. (Coleoptera: Derodontidae), predators of Adelgidae. *Insects* **10**, 426 (2019).
454. Yang, R. et al. Function of heat shock protein 70 in the thermal stress response of *Dermatophagoides farinae* and establishment of an RNA interference method. *Gene* **705**, 82–89 (2019).
455. Kamp, J., Trappe, J., Duebbers, L. & Funke, S. Impacts of windstorm-induced forest loss and variable reforestation on bird communities. *For. Ecol. Manag.* **478**, 118504 (2020).
456. Majdi, N., Uthoff, J., Traunspurger, W., Laffaille, P. & Maire, A. Effect of water warming on the structure of biofilm-dwelling communities. *Ecol. Indic.* **117**, 106622 (2020).
457. Marques-Santos, F. & Dingemanse, N. J. Weather effects on nestling survival of great tits vary according to the developmental stage. *J. Avian Biol.* <https://doi.org/10.1111/jav.02421> (2020).
458. Mutamiswa, R., Tarusikirwa, V., Nyamukondiwa, C. & Chidawanyika, F. Fluctuating environments impact thermal tolerance in an invasive insect species *Bactrocera dorsalis* (Diptera: Tephritidae). *J. Appl. Entomol.* **144**, 885–896 (2020).
459. Paalme, T., Torn, K., Martin, G., Kotta, I. & Suursaar, U. Littoral benthic communities under effect of heat wave and upwelling events in the Ne Baltic Sea. *J. Coast. Res.* **95**, 133–137 (2020).
460. Perneckner, B., Mauchart, P. & Csabai, Z. What to do if streams go dry? Behaviour of Balkan goldenring (*Cordulegaster heros*, Odonata) larvae in a simulated drought experiment in SW Hungary. *Ecol. Entomol.* **45**, 1457–1465 (2020).
461. Shiels, A. B., Lombard, C. D., Shiels, L. & Hillis-Starr, Z. Invasive rat establishment and changes in small mammal populations on Caribbean Islands following two hurricanes. *Glob. Ecol. Conserv.* **22**, e00986 (2020).
462. Truchy, A. et al. Habitat patchiness, ecological connectivity and the uneven recovery of boreal stream ecosystems from an experimental drought. *Glob. Change Biol.* **26**, 3455–3472 (2020).
463. van den Burg, M. P., Brisbane, J. L. K. & Knapp, C. R. Post-hurricane relief facilitates invasion and establishment of two invasive alien vertebrate species in the Commonwealth of Dominica, West Indies. *Biol. Invasions* **22**, 195–203 (2020).
464. Lavoie, M., Jenouvrier, S., Blanchette, P., Lariviere, S. & Tremblay, J.-P. Extreme climate events limit northern range expansion of wild turkeys. *Oecologia* **197**, 633–650 (2021).
465. Lombardero, M. J., Castedo-Dorado, F. & Ayres, M. P. Extreme climatic events affect populations of Asian chestnut gall wasps, *Dryocosmus kuriphilus*, but do not stop the spread. *Agric. Entomol.* **23**, 473–488 (2021).
466. Ma, G., Hoffmann, A. A. & Ma, C. S. Are extreme high temperatures at low or high latitudes more likely to inhibit the population growth of a globally distributed aphid? *J. Therm. Biol.* **98**, 102936 (2021).
467. Mantovano, T. et al. A global analysis of the susceptibility of river basins to invasion of a freshwater zooplankton (*Daphnia lumholzi*). *Freshw. Biol.* **66**, 683–698 (2021).
468. Marrack, L. et al. Assessing the spatial-temporal response of groundwater-fed anchialine ecosystems to sea-level rise for coastal zone management. *Aquat. Conserv.* **31**, 853–869 (2021).
469. Mills, R. & McGraw, K. J. Cool birds: facultative use by an introduced species of mechanical air conditioning systems during extremely hot outdoor conditions. *Biol. Lett.* <https://doi.org/10.1098/rsbl.2020.0813> (2021).

470. Nogueira, J. G., Lopes-Lima, M., Varandas, S., Teixeira, A. & Sousa, R. Effects of an extreme drought on the endangered pearl mussel *Margaritifera margaritifera*: a before/after assessment. *Hydrobiologia* **848**, 3003–3013 (2021).
471. Pazourkova, E. et al. Impacts of an extreme flood on the ecosystem of a headwater stream. *J. Limnol.* <https://doi.org/10.4081/jlimnol.2021.1998> (2021).
472. Perez, J., Correa-Araneda, F., Lopez-Rojo, N., Basaguren, A. & Boyero, L. Extreme temperature events alter stream ecosystem functioning. *Ecol. Indic.* **121**, 106984 (2021).
473. Rodgers, K. S. et al. Impact to coral reef populations at Ha'ena and Pila'a, Kaua'i, following a record 2018 Freshwater flood event. *Diversity* **13**, 66 (2021).
474. Simaz, O. & Szucs, M. Heat waves affect an invasive herbivore and its parasitoid differentially with impacts beyond the first generation. *Ecosphere* **12**, e03796 (2021).
475. Wehner, K., Simons, N. K., Bluethgen, N. & Heethoff, M. Drought, windthrow and forest operations strongly affect oribatid mite communities in different microhabitats. *Glob. Ecol. Conserv.* **30**, e01757 (2021).
476. Kirk, M. A., Maitland, B. M., Hickerson, B. T., Walters, A. W. & Rahel, F. J. Climatic drivers and ecological impacts of a rapid range expansion by non-native smallmouth bass. *Biol. Invasions* **24**, 1311–1326 (2022).
477. Kupferberg, S. J. et al. Seasonal drought and its effects on frog population dynamics and amphibian disease in intermittent streams. *Ecohydrology* **15**, e2395 (2022).
478. Liu, H., Wang, X., Chen, Z. & Lu, Y. Characterization of cold and heat tolerance of *Bactrocera tau* (Walker). *Insects* **13**, 329 (2022).
479. McDevitt-Galles, T., Moss, W. E. E., Calhoun, D. M. M., Briggs, C. J. J. & Johnson, P. T. J. How extreme drought events, introduced species, and disease interact to influence threatened amphibian populations. *Freshw. Sci.* **41**, 680–694 (2022).
480. McIntosh, A. R. Flood disturbance mediates the strength of stream trophic cascades caused by trout. *Limnol. Oceanogr. Lett.* **7**, 218–226 (2022).
481. Navarrete-Carballo, J. et al. Mosquito species (Diptera: Culicidae) collected after tropical storm Cristobal in Merida, Yucatan, South-east Mexico. *Int. J. Trop. Insect Sci.* **42**, 2007–2012 (2022).
482. Navas, C. A., Agudelo-Cantero, G. A. & Loeschcke, V. Thermal boldness: volunteer exploration of extreme temperatures in fruit flies. *J. Insect Physiol.* **136**, 104330 (2022).
483. Rilov, G., Klein, L., Iluz, D., Dubinsky, Z. & Guy-Haim, T. Last snail standing? Superior thermal resilience of an alien tropical intertidal gastropod over natives in an ocean-warming hotspot. *Biol. Invasions* **24**, 3703–3719 (2022).
484. Shiels, A. B. B., de Arellano, G. E. R. E. & Shiels, L. Invasive rodent responses to experimental and natural hurricanes with implications for global climate change. *Ecosphere* **13**, e4307 (2022).
485. Tao, W. et al. Heat wave induces oxidative damage in the Chinese pond turtle (*Mauremys reevesii*) from low latitudes. *Front. Ecol. Evol.* <https://doi.org/10.3389/fevo.2022.1053260> (2022).
486. Zhang, M., Wang, L., Li, J., Wang, Q. & Luo, A. Hail-induced mortality of Asian openbill (*Anastomus oscitans*) in southern tropical China. *Ecol. Evol.* **12**, e8983 (2022).
487. Roman, M. et al. Are clam–seagrass interactions affected by heatwaves during emersion? *Mar. Environ. Res.* **186**, 105906 (2023).
488. Shalders, T. C. et al. Impacts of seasonal temperatures, ocean warming and marine heatwaves on the nutritional quality of eastern school prawns (*Metapenaeus macleayi*). *Sci. Total Environ.* **876**, 162778 (2023).
489. Xu, X., Tong, Y., Deng, Y. & Zhao, L. Impacts of marine heatwaves on byssus production in highly invasive fouling mussels. *Mar. Environ. Res.* **184**, 105871 (2023).
490. Xu, X. et al. Survival and physiological energetics of highly invasive mussels exposed to heatwaves. *Mar. Environ. Res.* **187**, 105948 (2023).
491. Pedder, H., Sarri, G., Keeney, E., Nunes, V. & Dias, S. Data extraction for complex meta-analysis (DECIMAL) guide. *Syst. Rev.* **5**, 212 (2016).
492. Greco, T. et al. How to impute study-specific standard deviations in meta-analyses of skewed continuous endpoints? *World J. Metaanal.* **3**, 215–224 (2015).
493. van Aert, R. C. M., Wicherts, J. M. & van Assen, M. A. L. M. Publication bias examined in meta-analyses from psychology and medicine: a meta-meta-analysis. *PLoS ONE* **14**, e0215052 (2019).
494. Bonett, D. G. Meta-analytic interval estimation for standardized and unstandardized mean differences. *Psychol. Methods* **14**, 225–238 (2009).
495. Viechtbauer, W. Conducting meta-analyses in R with the metafor package. *J. Stat. Softw.* **36**, 1–48 (2010).
496. Hoaglin, D. C. Misunderstandings about Q and 'Cochran's Q test' in meta-analysis. *Stat. Med.* **35**, 485–495 (2016).
497. Lin, L. & Chu, H. Quantifying publication bias in meta-analysis. *Biometrics* **74**, 785–794 (2018).
498. Michael, B. L., Hedges, V., Higgins, J. P. T. & Rothstein, R. *Subgroup Analyses. Introduction to Meta-Analysis*, 149–186 (John Wiley & Sons, Inc., 2009).
499. Reynolds, S. A. & Aldridge, D. C. Global impacts of invasive species on the tipping points of shallow lakes. *Glob. Change Biol.* **27**, 6129–6138 (2021).
500. Viechtbauer, W. & Cheung, M. W.-L. Outlier and influence diagnostics for meta-analysis. *Res. Synth. Methods* **1**, 112–125 (2010).
501. Lin, L., Chu, H. & Hodges, J. S. Alternative measures of between-study heterogeneity in meta-analysis: reducing the impact of outlying studies. *Biometrics* **73**, 156–166 (2017).
502. GBIF Occurrence Download (GBIF, last accessed date 21 May 2023); <https://www.gbif.org/user/download?offset=0&limit=20>
503. Chamberlain, S. *scrubr: Clean Biological Occurrence Records (R Package v.0.3.2)* (The Comprehensive R Archive Network, 2020).
504. Aiello-Lammens, M. E., Boria, R. A., Radosavljevic, A., Vilela, B. & Anderson, R. P. spThin: an R package for spatial thinning of species occurrence records for use in ecological niche models. *Ecography* **38**, 541–545 (2015).
505. Steen, V. A., Tingley, M. W., Paton, P. W. C. & Elphick, C. S. Spatial thinning and class balancing: key choices lead to variation in the performance of species distribution models with citizen science data. *Methods Ecol. Evol.* **12**, 216–226 (2021).
506. Guisan, A., Thuiller, W. & Zimmermann, N. E. *Habitat Suitability and Distribution Models: With Applications in R* (Cambridge Univ. Press, 2017).
507. Phillips, S. J. & Dudik, M. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography* **31**, 161–175 (2008).
508. Zurell, D. et al. A standard protocol for reporting species distribution models. *Ecography* **43**, 1261–1277 (2020).
509. Hao, T., Elith, J., Lahoz-Monfort, J. J. & Guillera-Arroita, G. Testing whether ensemble modelling is advantageous for maximising predictive performance of species distribution models. *Ecography* **43**, 549–558 (2020).
510. Li, Y., Liu, X., Li, X., Petitpierre, B. & Guisan, A. Residence time, expansion toward the equator in the invaded range and native range size matter to climatic niche shifts in non-native species. *Glob. Ecol. Biogeogr.* **23**, 1094–1104 (2014).
511. Tingley, R., Vallinoto, M., Sequeira, F. & Kearney, M. R. Realized niche shift during a global biological invasion. *Proc. Natl Acad. Sci. USA* **111**, 10233–10238 (2014).

512. Warren, D. L., Glor, R. E. & Turelli, M. ENMTools: a toolbox for comparative studies of environmental niche models. *Ecography* **33**, 607–611 (2010).
513. Phillips, S. J. et al. Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data. *Ecol. Appl.* **19**, 181–197 (2009).
514. Liu, X. et al. Animal invaders threaten protected areas worldwide. *Nat. Commun.* **11**, 2892 (2020).
515. Assis, J. et al. Bio-ORACLE v2.0: extending marine data layers for bioclimatic modelling. *Glob. Ecol. Biogeogr.* **27**, 277–284 (2018).
516. Basher, Z., Bowden, D. A. & Costello, M. J. *Global Marine Environment Datasets Version 2.0* (GMED, accessed December 2021); <http://gmed.auckland.ac.nz>
517. Hoegh-Guldberg, O. & Bruno, J. F. The impact of climate change on the world's marine ecosystems. *Science* **328**, 1523–1528 (2010).
518. Moore, C. H., Harvey, E. S. & Van Niel, K. P. Spatial prediction of demersal fish distributions: enhancing our understanding of species–environment relationships. *ICES J. Mar. Sci.* **66**, 2068–2075 (2009).
519. Reiss, H., Cunze, S., König, K., Neumann, H. & Kröncke, I. Species distribution modelling of marine benthos: a North Sea case study. *Mar. Ecol. Prog. Ser.* **442**, 71–86 (2011).
520. Lenoir, S., Beaugrand, G. & Lecuyer, É. Modelled spatial distribution of marine fish and projected modifications in the North Atlantic Ocean. *Glob. Change Biol.* **17**, 115–129 (2011).
521. Langbehn, T. J. & Varpe, Ø. Sea-ice loss boosts visual search: fish foraging and changing pelagic interactions in polar oceans. *Glob. Change Biol.* **23**, 5318–5330 (2017).
522. Wang, L. et al. Modeling marine pelagic fish species spatiotemporal distributions utilizing a maximum entropy approach. *Fish. Oceanogr.* **27**, 571–586 (2018).
523. Dormann, C. F. et al. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography* **36**, 27–46 (2013).
524. Reid, B. N. et al. Disentangling the genetic effects of refugial isolation and range expansion in a trans-continently distributed species. *Heredity* **122**, 441–457 (2019).
525. Castellanos, A. A., Huntley, J. W., Voelker, G. & Lawing, A. M. Environmental filtering improves ecological niche models across multiple scales. *Methods Ecol. Evol.* **10**, 481–492 (2019).
526. Strubbe, D., Beauchard, O. & Matthysen, E. Niche conservatism among non-native vertebrates in Europe and North America. *Ecography* **38**, 321–329 (2015).
527. Hirzel, A. H., Le Lay, G., Helfer, V., Randin, C. & Guisan, A. Evaluating the ability of habitat suitability models to predict species presences. *Ecol. Modell.* **199**, 142–152 (2006).
528. Swets, J. A. Measuring the accuracy of diagnostic systems. *Science* **240**, 1285–1293 (1988).
529. Allouche, O., Tsoar, A. & Kadmon, R. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *J. Appl. Ecol.* **43**, 1223–1232 (2006).
530. Muscarella, R. et al. ENMeval: an R package for conducting spatially independent evaluations and estimating optimal model complexity for Maxent ecological niche models. *Methods Ecol. Evol.* **5**, 1198–1205 (2014).
531. Dunn, R. J. H. et al. Development of an updated global land in situ-based data set of temperature and precipitation extremes: HadEX3. *J. Geophys. Res. Atmos.* **125**, e2019JD032263 (2020).
532. Argüeso, D., Di Luca, A., Perkins-Kirkpatrick, S. E. & Evans, J. P. Seasonal mean temperature changes control future heat waves. *Geophys. Res. Lett.* **43**, 7653–7660 (2016).
533. Russo, S. et al. Magnitude of extreme heat waves in present climate and their projection in a warming world. *J. Geophys. Res. Atmos.* **119**(12), 500–12,512 (2014).
534. Tanaka, K. R. & Van Houtan, K. S. The recent normalization of historical marine heat extremes. *PLOS Clim.* **1**, e0000007 (2022).
535. Wang, Y., Kajtar, J. B., Alexander, L. V., Pilo, G. S. & Holbrook, N. J. Understanding the changing nature of marine cold-spells. *Geophys. Res. Lett.* **49**, e2021GL097002 (2022).
536. Ward, P. J. et al. *Aqueduct Floods Methodology* Technical Note (World Resources Institute, 2020).
537. McKee, T. B., Doesken, N. J. & Kleist, J. R. The relationship of drought frequency and duration to time scales. *Proc. 8th Conf. Appl. Climatol.* **17**, 179–183 (1993).
538. Hijmans, R. J. et al. *Raster Package in R (R Package v.3.5-21)* (The Comprehensive R Archive Network, 2013).
539. Gearty, W. & Jones, L. A. rphylopic: an R package for fetching, transforming, and visualising PhyloPic silhouettes. *Methods Ecol. Evol.* **00**, 1–9 (2023).
540. Gu, S., Qi, T., Rohr, J. R. & Liu, X. Meta-analysis reveals less sensitivity of non-native animals than natives to extreme weather worldwide. *Figshare* <https://doi.org/10.6084/m9.figshare.23587695> (2023).
541. R Core Team. *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, 2022).

Acknowledgements

X.L. was supported by the Third Xinjiang Scientific Expedition Program (2022xjkk0800 and 2021xjkk0600), the National Science Foundation of China (32171657), grants from the Youth Innovation Promotion Association of the Chinese Academy of Sciences (Y201920) and grants from the High Quality Economic and Social Development in Southern Xinjiang (NFS2101). J.R.R. was supported by funding provided by the US National Science Foundation (EEID-1518681, DEB-2017785) and the US Department of Agriculture (NRI 2009-35102-0543).

Author contributions

X.L. conceived the project. X.L., S.G. and J.R.R. designed the study. X.L. supervised the project. S.G., T.Q. and X.L. collected the data. S.G., T.Q. and X.L. performed data analyses. S.G. and X.L. wrote the manuscript draft and all authors contributed to manuscript revisions.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41559-023-02235-1>.

Correspondence and requests for materials should be addressed to Xuan Liu.

Peer review information *Nature Ecology & Evolution* thanks Tim Doherty and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Peer reviewer reports are available.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

© The Author(s), under exclusive licence to Springer Nature Limited 2023

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our [Editorial Policies](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a Confirmed

- The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
- A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
- The statistical test(s) used AND whether they are one- or two-sided
Only common tests should be described solely by name; describe more complex techniques in the Methods section.
- A description of all covariates tested
- A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
- A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
- For null hypothesis testing, the test statistic (e.g. F , t , r) with confidence intervals, effect sizes, degrees of freedom and P value noted
Give P values as exact values whenever suitable.
- For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
- For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
- Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection

A total of 443 studies used for meta-analysis were collected from two sources. One source comes from conducting a systematic literature search through a variety of search engines such as Clarivate Web of Science and Scopus. Full details of the search terms and filtering criteria were included in the Supplementary Methods. Another source comes from recent reviews and syntheses of Maxwell et al. 2018, Neilson et al. 2020, Thakur et al. 2022, and Sabater et al. 2023. Occurrence records of non-native species were gathered from the online database of the Global Biodiversity Information Facility and added additional records from the literature. Bioclimatic variables were downloaded from the WorldClim-Global Climate Database. Habitat factors included vegetation and water cover variables. The vegetation cover variable referred to the annual normalised difference vegetation index (NDVI) and was collected from the Nasa Earth Observations. The water cover variable was collected from the global lakes and wetlands database. Marine environmental variables were collected from Bio-ORACLE database. Sea water depth information was collected from Global Marine Environment Datasets. Heatwave and cold-spell events on terrestrial and freshwater ecosystems were collected from HadEX3 database. Marine heatwave events were collected from Tanaka and Van Houtan (2022)'s layer data. Marine cold-spell events were collected from Wang et al (2022)'s layer data. Storm events were collected from the Global Risk Data Platform. Extreme Flood events were collected from the Aqueduct Flood Hazard Maps database. Extreme drought events were collected from the National Center for Atmospheric Research (NCAR)/University Corporation for Atmosphere Research (UCAR) platform. Full detail information for all data sources were provided in Supplementary Methods.

Data analysis

All data analysis was completed using R version 4.2.1. All packages used are fully referenced in the Supplementary methods.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

We confirm that the data supporting the results are available in a public structured data depository.

Human research participants

Policy information about [studies involving human research participants and Sex and Gender in Research](#).

Reporting on sex and gender

n/a

Population characteristics

n/a

Recruitment

n/a

Ethics oversight

n/a

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

Life sciences Behavioural & social sciences Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://www.nature.com/documents/nr-reporting-summary-flat.pdf)

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description

Extreme weather events (EWEs) and non-native species invasions have devastating impacts on native biodiversity and their joint effects would be a greater threat to native species. However, there is still lack of a general evaluation of the effects of EWEs on non-native species for multiple taxonomic groups across ecosystems and types of EWEs, which is critically important to predict non-native species responses to climate change and evaluate global hotspots of their potential joint effects. Here, we conducted a global synthesis of comparing the responses of non-native and native animal species to extreme weather events. We then calculated the net effect of each non-native animal to EWEs in each overlapped grid as the proportions of positive plus neutral responses minus negative response based on the sample effect sizes in the meta-analyses above. The accumulative net effect for each grid was obtained to reflect the overall tolerance of all potential non-native species to EWEs. A list of EWE tolerant non-native species was determined. Furthermore, we displayed overlaps between hotspots of non-native species and EWEs to identify locations where native species might be adversely affected by their joint effects.

Research sample

Following our criteria, all relevant studies were included and involved mammals, birds, amphibians, reptiles, fish, and invertebrates to five types of EWEs across terrestrial, freshwater, and marine ecosystems. In total we report 5,303 effect sizes for 973 non-native species and 4,330 native animal species from 443 studies.

Sampling strategy

We used terms to search published research literatures from ISI Web of Science (all databases) and Scopus (in "All fields") across all years (last accessed date: 24 April 2023). We removed duplicate publications from different searching sources. The remaining publications were related to research articles, animal species studying system, and available quantifications of extreme weather events (EWEs)' effects on the animal species. As a result, a list of non-native and native animal species could be determined. Based the Class identity and experienced types of EWEs of non-native species, we finally analyzed native species with the same class level and experienced EWEs' type.

Data collection

A total of 443 studies were used for meta-analysis. In those studies, when the data used for calculating sample effect sizes were directly reported in the text, we recorded the data in Excel for next analysis. When the data were not directly reported in the text but in figures, we used GetData graph Digitizer (version 2.24) to extract values. Sample size, mean and variance values in control and treatment groups were extracted from each study. Details of other variables in analysis were also extracted and reported in the Supplementary Methods. Occurrence records of non-native species were downloaded from the Global Biodiversity Information Facility. We used latin names of non-native species to search literatures on ISI Web of Science to add additional records. We further excluded those records without precise coordinates and unclear establishment status. We removed duplicate coordinates. The occurrence data were thinned to 5 arcmin resolution (~9.2 km at the equator) to reduce sampling bias from disproportional survey

efforts among taxa or regions. Distribution layers of different types of EWEs were downloaded from open data sources and publications. Details of available resolution of the layers and cited sources were described in Supplementary Methods.

Timing and spatial scale

The literature was searched by 24 April 2023. Occurrence records of non-native species were downloaded from the Global Biodiversity Information Facility which was last accessed at 21 May 2023. Heatwave and cold-spell events on terrestrial and freshwater ecosystems were collected from HadEX3 database during 1901 to 2018. Marine heatwave events were collected from Tanaka and Van Houtan (2022)'s layer data during 1980 to 2019. Marine cold-spell events were collected from Wang et al (2022)'s layer data during 1982 to 2020. Storm events were collected from the Global Risk Data Platform during 1970 to 2015. Extreme Flood events were collected from the Aqueduct Flood Hazard Maps database during 1979 to 2014. Extreme drought events were collected from the National Center for Atmospheric Research (NCAR)/University Corporation for Atmosphere Research (UCAR) platform during 1950 to 2012. All Literature search and data downloads were conducted on a global scale.

Data exclusions

Papers were excluded where they did not meet our inclusion criteria specified in the Supplementary Methods. We include a detailed PRISMA chart of all exclusion (Supplementary Fig. 1).

Reproducibility

All data sources have been provided in the Supplementary Methods, and we will additionally make all original data public in a structured data depository upon the publication of the work.

Randomization

This is not relevant to this study as the data was collected from existing studies and is already allocated as either treatment or control.

Blinding

Blinding was not carried out as part of this study. All data were extracted from existing treatment and control studies therefore it was not necessary or possible to blind ourselves during this extraction.

Did the study involve field work? Yes No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

- n/a | Involved in the study
- Antibodies
 - Eukaryotic cell lines
 - Palaeontology and archaeology
 - Animals and other organisms
 - Clinical data
 - Dual use research of concern

Methods

- n/a | Involved in the study
- ChIP-seq
 - Flow cytometry
 - MRI-based neuroimaging