# Cross-realm assessment of climate change impacts on species' abundance trends

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**Climate change, land-use change, pollution and exploitation are among the main drivers of species' population trends; however, their relative importance is much debated. We used a unique collection of over 1,000 local population time series in 22 communities across terrestrial, freshwater and marine realms within central Europe to compare the impacts of long-term temperature change and other environmental drivers from 1980 onwards. To disentangle different drivers, we related species' population trends to species- and driver-specific attributes, such as temperature and habitat preference or pollution tolerance. We found a consistent impact of temperature change on the local abundances of terrestrial species. Populations of warm-dwelling species increased more than those of cold-dwelling species. In contrast, impacts of temperature change on aquatic species' abundances were variable. Effects of temperature preference were more consistent in terrestrial communities than effects of habitat preference, suggesting that the impacts of temperature change have become widespread for recent changes in abundance within many terrestrial communities of central Europe.**

Analyses of long-term trends in species' populations, such as the Living Planet Index, show global declines in abundances[1,2]. Understanding the cause of changes in species' abundances is crucial to assess consequences for ecosystem functioning[3], range shifts[4] and extinction risk, and for making conservation decisions[5]. Much research has focused on the possible future impacts[6] of climate change, but climate change has already affected species in multiple ways, with range shifts detected in diverse taxa[7,8]. Species' abundances are potentially more sensitive to climate change than range boundaries—a binary presence/absence change in abundance[9,10]. However, the effects of climate change that have already occurred on species' abundances are much less recognized. Population abundances are affected by many environmental drivers, including habitat loss and degradation, along with pollution, invasive species and exploitation[1,2,11]. Until now, the impact of climate change on population trends and how it compares with other large-scale drivers has not been assessed across major taxonomic groups and environmental realms.

Temporal changes in the abundances of organisms have been used to infer the impact of particular environmental drivers on communities. For instance, the effect of nitrogen pollution on a particular lichen species depends on its species-specific nitrogen tolerance.

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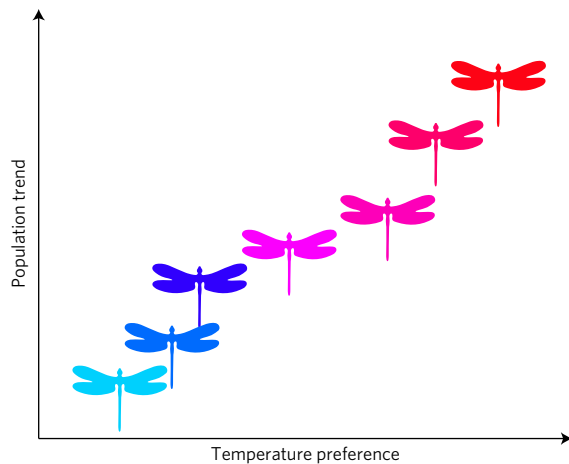
**Figure 1 | Relationship between species' temperature preferences and population trends under climate change.** Each dragonfly represents a species; temperature preference is reflected in the colour shading from warm (red) to cool (blue). If climate change is an important driver of long-term population trends, we predicted a positive relationship between species temperature preference and long-term population trend. This approach is a short-cut to understanding the effect of climate change (environmental change) on a community by assuming that species vary in their response according to their particular temperature preference (species attribute). This framework can be generalized to test the effects of other environmental change using the most relevant species attribute.

Consequently, declines in the abundance of nitrogen-sensitive lichens have been used as a bioindicator of pollution[12]. Thus, given sufficiently detailed species-level knowledge, differential population trends of species according to their particular attributes (that is, specific characteristics of the species) can be used as a bioindicator of the impacts of environmental change. Such attribute-based approaches have a number of advantages. First, they integrate the effects of the components of environmental change that are most relevant to the organism, when environmental data often are either not available or complex to summarize. For example, declines of farmland birds have highlighted the negative impacts of agricultural intensification, mediated by various changes, including seasonal land-use practices, and fertilizer and pesticide usage[13,14]. Second, observed species' responses integrate the effects of environmental change at the spatial and temporal scales that matter to the organism, for instance if effects act within particular time windows[15] or spatial scales[16].

We used a species attribute-based approach to test for signals of long-term temperature change on the abundances of species within terrestrial, freshwater and marine communities. In broad terms, we first aimed to detect population trends and then to attribute these trends to long-term temperature change[17]. If temperature change had affected abundances, we expected that some species had increased or that others had decreased. Changes in abundances can be driven by many factors, but long-term trends of abundance are most probably due to deterministic factors such as the persistent effects of a long-term change in the environment. Although such trends may correlate with temperature trends, they may also correlate with trends in other long-term drivers of biodiversity change. To attribute the population trends to temperature change, we related the variation in population trends within each community to species' temperature preferences. Because the impact of temperature change on a species can be predicted to depend on its temperature preference, more positive trends of warm-dwelling species over cold-dwelling species within each community imply a signal of climate change. Thus, we used the strength of the relationship between species' temperature preferences and long-term population trends within each community as an indicator of climate change (Fig. 1).

We applied our approach to 22 long-term local or regional community datasets within central Europe, including abundance data for taxa from 40 classes (from algae to mammals). This represents, to our knowledge, the most taxonomically diverse analysis on population trends in Europe to date. Each dataset comprised 9–130 species for which population data were collected over a 12–34 year time span (1980 onwards) (Fig. 2a and Supplementary Tables 1 and 2). The datasets cover a broad range of habitats (forest, agricultural land, grassland, sand dunes, wetland, heathland, lakes, rivers, sea), but we cannot assume they are truly representative—long-term sampling is rarely done in highly disturbed environments. Our study profits from the inclusion of groups that are rarely studied in climate change assessments, such as soil invertebrates, which might show different responses from commonly studied mobile taxa, such as birds.

For each species, we calculated its long-term population trend and its temperature preference using European distribution data and average temperature maps. For each community dataset, we built regression models that related population trends to species attributes affecting sensitivity to particular environmental drivers (see Table 1; temperature preference for temperature change, habitat preference for land-use change, pollution tolerance (for example, nitrogen tolerance) for pollution). The regression models also included attributes that might further modify species' responses (such as habitat breadth and dispersal ability, affecting the adaptive capacity of individuals, and life span or age at maturity, affecting population resilience)[18] (Supplementary Fig. 1 shows an outline of the methods and Supplementary Table 3 shows the attributes tested for each dataset).

Regression statistics from each dataset were combined together by meta-analysis, allowing control of dataset-level effects such as number of species and sampling sites, start year, time span and temperature trend over the study period (Supplementary Table 4). From this combined analysis, we tested (1) whether the temperature preferences of species are generally positively associated with their population trends, as a signal of the impact of climate change in terrestrial, freshwater and marine realms, and (2) the relative strengths of these climate change signals compared with those of land-use change, pollution and exploitation.

## Results

Average annual temperatures in the study areas had increased (mean ± s.e.m., $0.33 \pm 0.07\,°C$ decade$^{-1}$; Supplementary Fig. 2 and Supplementary Table 5) and this trend did not significantly differ among realms. Local temperature trends for each dataset were not always significant over the time period of data collection, but they pointed towards positive trends when analysed since the 1980s (Supplementary Table 5). Overall, almost half of the species' populations showed a significant abundance trend (47%, 552/1,167; Supplementary Fig. 3). The percentage of populations with significant trends was 61% (132/216) in the marine realm, 48% (323/680) in the terrestrial realm and 35% (97/271) in the freshwater realm. Positive trends, that is, increases of abundance, were more common in the marine and terrestrial realm (62% and 60% of the significant trends, respectively), while negative trends were more frequent (60%) in the freshwater realm.

Averaging across all datasets, there was a significant relationship between species' temperature preferences and population trends (correlation coefficient ($r$) = 0.164, 95% confidence interval (CI) = 0.095, 0.234). Although the difference among realms was not statistically significant, only the effect in the terrestrial communities had a CI that did not overlap zero (Fig. 2b; $r$ = 0.165, 95% CI = 0.046, 0.280; predicted at average start year, number of species and sampling sites). Thus, population trends were positively related with temperature preferences in terrestrial communities; that is, populations
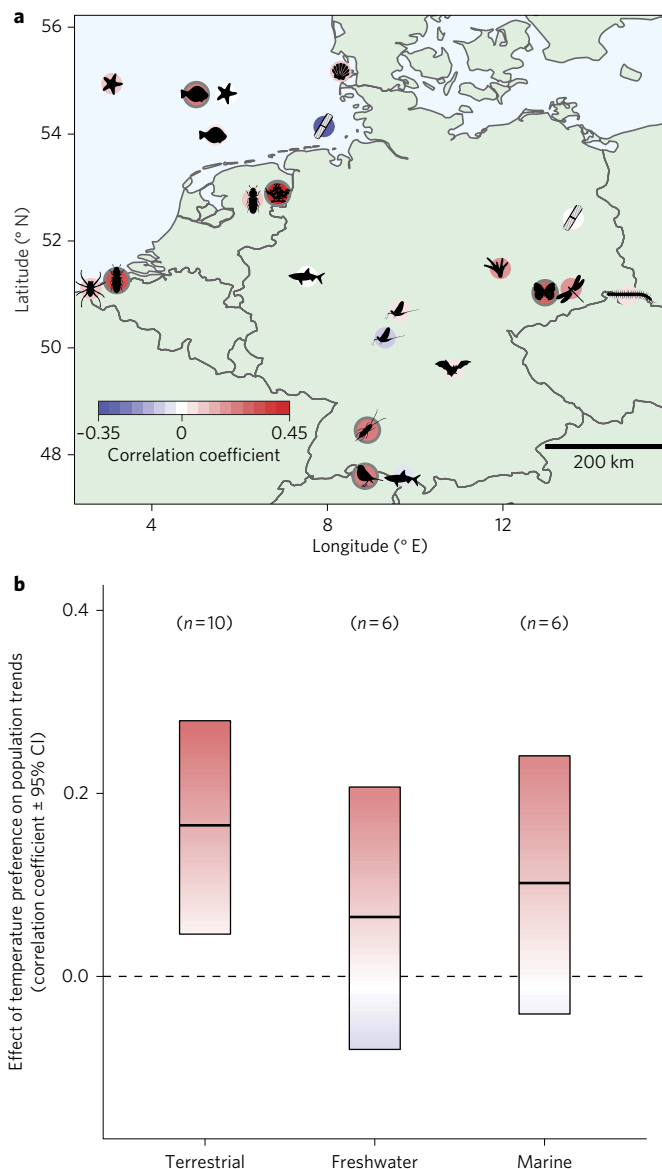
**Figure 2 | Climate change impacts on local communities. a**, The geographic location of each dataset (symbols explained in Supplementary Fig. 3) within central Europe; the colours behind the symbols represent the strength to which each community shifted towards warm (pink) or cold-dwelling species (blue) (that is, the correlation coefficient of the relationship between temperature preference and population trend). Significant effects are circled with a dark grey outline. **b**, The modelled average effect size (correlation coefficient ± 95% CI) of temperature preference on population trends in each realm, predicted at average start year, log number of sampling sites and log number of species across all datasets.

of species with warmer temperature preferences increased more than those of species with colder temperature preferences. We found the strongest evidence of impacts for the bird, butterfly, ground beetle, springtail and lichen datasets (Supplementary Fig. 4). In contrast, average effects were not significant in the freshwater and marine communities, although we detected a signal in the marine fish dataset (Fig. 2).

Such differences among realms might partly exist because some of the time series from the freshwater and marine communities were shorter, having begun more recently, reflecting the lesser extent of aquatic long-term monitoring. However, average realm effects were robust and independent of dataset characteristics (start year, number

of species and sampling sites) as well as of different data weightings or subsampling (Supplementary Figs 5 and 6). Pooling together the freshwater and marine data to achieve similar numbers of datasets (terrestrial, $n = 10$; aquatic, $n = 12$) still gave an average insignificant effect across the aquatic communities, but it did tend to be positive (aquatic effect size: 0.08, 95% CI = −0.01, 0.18; predicted at average start year, number of species and sampling sites).

To examine whether the relationship between temperature preference and population trend was mostly driven by increases of warm-dwelling species or decreases of cold-dwelling species, we tested whether species in the upper and lower temperature preference quartiles had positive and negative trends, respectively. Increases of warm-dwelling species were found for birds, butterflies, springtails and lichens as well as marine fish, while decreases of cold-dwelling species were only seen in birds and ground beetles (Supplementary Fig. 7). On average across terrestrial species, warm-dwelling species had increased (difference of trends from zero, $z$-score ($z$) = 2.26, $P = 0.02$), while aquatic warm-dwelling species had not ($z = −0.27$, $P = 0.78$).

Although habitat preferences were significant for some taxa, such as farmland birds (Supplementary Fig. 8), the average effect across all ten terrestrial communities did not reach statistical significance ($z = 1.54$, $P = 0.12$; Fig. 3). There was an effect of pollution tolerance in lichen communities ($z = 4.21$, $P < 0.01$), with increases of nitrophilous species[19], but not in the plant community; this was not tested for the other eight datasets because of a lack of information on nitrogen/nutrient preferences. In contrast, in freshwater communities, species preferring low-nutrient environments had more positive population trends ($z = −2.37$, $P = 0.02$; Fig. 3). Effects of exploitation were detected for marine fish ($z = −3.99$, $P < 0.01$), but not for freshwater fish ($z = −1.19$, $P = 0.24$). Commercially exploited marine fish had less positive population trends than non-commercial fish (Fig. 3).

## Discussion

We tested for climate change signals on population trends across the broadest range of taxa in Europe to date. The long-term increases and decreases of species' abundances provided evidence for a long-term driver affecting these communities. Based on the relationship between species' temperature preferences and population trends, we interpret our results as showing an average effect of temperature change in the terrestrial communities and more variable effects in the aquatic communities.

Although other routes through which climate change might affect communities, such as biotic interactions, are increasingly debated[20], our findings suggest that direct effects of warming are widely important in the terrestrial realm. Habitat loss, fragmentation and degradation are among the leading causes of biodiversity loss in the past century. However, land conversion to cropland peaked in the 1950s[21]. Although past land-use change is still of great importance for spatial patterns of species' abundances, it may be less so for recent temporal changes of abundance within the remaining local communities of central Europe. Our terrestrial datasets may be biased towards areas where land-use change has been low, but recent effects of land-use change might be now limited to specific localities, where change is still occurring, and to particular taxa, such as farmland birds[22] and grassland butterflies[23], being affected by such change. Indeed, recent changes in the human footprint, based on human population size, land use and infrastructure, suggest an improvement (using data between 1993 and 2009) in many parts of Europe[24]. In contrast, communities in most localities are experiencing some temperature change, suggesting that the impacts of climate change are now more geographically widespread than those of land-use change.

For aquatic communities, the higher heat capacity of water may buffer aquatic systems from rapid temperature changes. However,

**Table 1 | Hypotheses regarding which species attributes modify the response of species to different environmental drivers.**

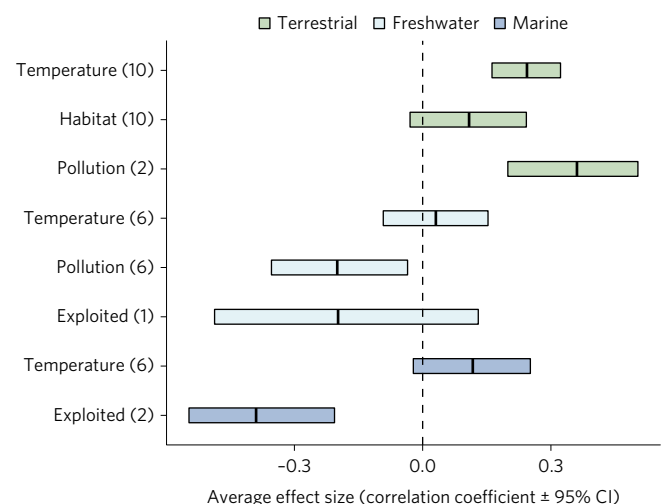| Environmental driver | Modifying species attribute | Hypothesis if driver is important for long-term population trends |
|---|---|---|
| Long-term temperature change | Temperature preference | More positive trends of warm-dwelling species over cold-dwelling species (Fig. 1). |
| Land-use change | Habitat use or breadth | More positive trends of species whose habitats have expanded or matured (for example, forest), have been less affected by human activities (for example, not farmland) or are habitat generalists. |
| Pollution | Nitrogen/pollution tolerance | More positive trends of species with a preference for or tolerance of nutrient-rich conditions. |
| Over-exploitation | Exploited or not | More positive trends of unexploited species over exploited species. |

this would not prevent long-term changes and, like others[25], we did find a climate change signal in marine fish. Patterns from local freshwater fish and benthic invertebrate communities in France[26,27] have also suggested community shifts towards warm-dwelling or thermally tolerant species, which we did not observe in our freshwater datasets. Impacts on aquatic groups might be locally variable, depending on the landscape context. Other long-term environmental drivers, especially changes in external nutrient load, may have overridden any effects of temperature change on long-term population trends in the communities in our analysis. This driver was suggested by the effect of pollution-related attributes on the population trends of freshwater species and is consistent with recent declines in nutrient loads of lakes and rivers in Europe[28] (an outcome of improved wastewater treatment). As information on pollution-related attributes was missing for many freshwater species, this community shift should be re-assessed as additional data become available. Exposure to weaker temperature change in the marine and freshwater communities would also explain the less consistent climate change signal in these communities. Although this interpretation was not supported by annual time series of average daily temperatures from the sites, this summary variable might not capture the temperature change relevant for aquatic organisms. Our analysis also does not exclude climate change impacts in aquatic systems being mediated by alternative routes, for instance, by changes in river discharge[27] and patterns of thermal stratification[29].

Our cross-dataset assessment suggests that effects of temperature change may differ between terrestrial and aquatic communities. Temperature preference was the most consistent predictor of recent population trends in the terrestrial realm, indicating that temperature change is important for different kinds of organisms in different localities. Similar in philosophy, the Community Temperature Index has also been used to show increases in the proportion of warm-dwelling species over cold-dwelling ones, especially for birds and butterflies[10,30], as an indicator of climate change impacts. However, by using a multiple regression approach, our approach simultaneously accounted for the effects of other species attributes (see Supplementary Table 3) on population abundance before interpreting the effect of species temperature preference. This approach provides more confidence that any estimated effects are due to temperature change rather than some other driver[31].

The simplicity of our approach meant it was practical enough to be applied across a broad range of species. However, there are many challenges to cross-taxa analysis. As much as possible, we have corrected for effects of variation in dataset attributes on our findings, but continued sampling, especially in freshwater and marine communities, which have been less sampled, is essential. Inferring species temperature preferences from coarse distribution is complicated by differences between species' fundamental and realized niches[32] and microclimatic variation[33]. In particular, estimating the thermal tolerances of freshwater organisms is hindered by the lack of large-scale freshwater water temperature maps. Including physiological measurements of species' thermal tolerances would strengthen the conclusions that could be made from our approach,

but such data are limited to few species. Unfortunately, the data available (on populations, distributions and species attributes) for different taxa still varies in quality; it is most probably of the highest quality for birds. Although trait databases are now being developed for organisms such as beetles[34] and soil organisms[35], there is still less, and more variable quality, information available for invertebrates. Because we were able to estimate temperature preference of organisms on a finer scale than habitat preference, this might have increased our ability to detect temperature effects over habitat effects. However, even coarsening the temperature preference data (comparing species in the upper tertile versus those in the lower tertile of temperature preferences; Supplementary Fig. 9) still suggested that warm-dwelling species had more positive population trends than cold-dwelling species in the terrestrial communities. Finally, it is important to emphasize that we focused on the effects of temperature change on recent population trends. An absence of an effect on population trends does not rule out species responding to climate change in some other way, such as phenology[36].

Although vital to inform assessments of the Convention on Biological Diversity targets and for conservation decision-making, long-term datasets on population abundances remain scarce. Clearly, land-use change was the predominant factor affecting terrestrial communities during the twentieth century. Our conclusions



**Figure 3 | Impacts of environmental drivers on population trends.** Crossbars are average effect sizes (correlation coefficient ± 95% CI) of species attributes related to temperature preference, habitat preference (mediating response to land-use change), pollution tolerance and exploitation, as predictors of population trends in terrestrial (green), freshwater (light blue) and marine (dark blue) communities. Number of datasets used are shown in brackets (for pollution, only lichens and plants were included in the terrestrial datasets; for exploitation, only fish were included in the aquatic datasets).

are restricted to changes in local communities over the past two or three decades and concern which drivers have been more widespread. Land-use change has the potential to strongly affect local communities, but its impacts are spatially variable. Our results suggest that many communities have been less exposed to and less affected by land-use change over this time period than previously. In contrast, climate change is a widespread driver and thus has the potential to affect populations over a large scale. We find stronger evidence that climate change has affected the recent abundance changes within many central European terrestrial communities, compared with aquatic communities, particularly leading to increases of species with warm temperature preferences.

## Methods

**Population data.** We compiled long-term datasets with at least four census years since 1980 (average number of census years = 19) within a geographical extent of central Europe and the southern part of the North Sea—the majority of the data were from standardized scientific surveys, but in a few cases they were sourced from citizen science or government agency monitoring programmes (see Supplementary Table 1).

**Rationale of approach.** Supplementary Fig. 1 shows an outline of the methods. We analysed each dataset in a way that was as similar as possible, to determine the signals of long-term temperature change and other environmental drivers that could be detected. It was not possible to analyse the individual datasets in exactly the same way throughout because some datasets had additional issues; for example, variation in sampling effort or within-year sampling. In addition, we wanted to ensure that our patterns were not driven by a few common species. The most important steps of our analysis were fitting a population trend for each species in each dataset (Supplementary Fig. 1, step c), estimating the effect of species attributes on population trends within each community using regression (Supplementary Fig. 1, step d) and bringing the individual dataset regression results together by meta-analysis (Supplementary Fig. 1, step f). We took this stepwise approach so that we could (1) modify the fitting of population trends to account for details of each dataset (for example, addition of sampling effort offset term or month of sampling fixed effect, when appropriate) and (2) examine patterns at the species level and test the effect of weighting species data points by the confidence of the trends, so that we could ensure that patterns were not driven by a few common species within each dataset.

**Prior subsetting.** Before analysis, we restricted the data to 1980 onwards and species seen in at least 25% of census years (Supplementary Table 2). The analysis was also repeated using a higher threshold for species occurrence, which yielded similar results (Supplementary Figs 6 and 10).

**Population trends.** We calculated the population trend of each species as its average annual population growth. In the standard analysis, these trends were estimated using a generalized linear model with Poisson errors including year (a continuous variable) and site (a factor) as predictor variables, as well as an autoregressive term to account for residual autocorrelation of counts as a function of time between censuses and an additional observation-level error term to account for any overdispersion, which was fitted by Bayesian inference using R-INLA (http://www.r-inla.org/)[37]. Because we were interested in the species long-term trend, we only considered the linear trend over time. An 'effort' offset term was included in the model when appropriate. A significant population trend was identified when the trend estimate was significantly different from zero (except in one case (birds), when it was inferred from consistent direction of change between each decadal census). See Supplementary Table 1 for deviations to this standard analysis.

**Species temperature preference.** We approximated each species temperature preference using distribution data (see Supplementary Table 3 for the distribution data sources used for each taxonomic group). As much as possible we aimed to get range maps (that is, polygons); when this was not possible, we used point occurrence records from the Global Biodiversity Information Facility (GBIF), the Ocean Biographic Information System (OBIS) or country checklist data. Our aim with the calculation of temperature preference was to create a variable that reflected the rank and relative differences of species towards warmer and cooler temperatures, and not necessarily species' optimal performance temperatures. Thus, using restricted and coarse distribution data should be sufficient for this purpose. Using temperature data maps delineated to Europe, we extracted the grid temperatures from locations intersecting with the distribution of each species. We restricted calculation to a European temperature map because, for most species, the best distribution data available were restricted primarily to Europe. For terrestrial and freshwater datasets, we used temperature maps from the E-Obs gridded dataset[38] of average temperature between 1961 and

1990, projected onto a 25 km equal area grid. Although ideally we would have used water temperature for the freshwater datasets, such European-wide freshwater temperature data are not readily available and air temperature data are commonly used. In addition, air and water temperature are highly correlated[39]. For the marine datasets, we used sea surface (for plankton) and bottom surface (for benthic invertebrates and fish) temperature maps from Aquamaps on a 50 km equal area grid (according to availability: 1982–1999 for sea surface temperature; 1990–1999 for bottom surface temperature)[40]. For dragonflies, data were already available[41] on a 50 km grid, so we used this resolution for them. For butterflies, temperature preference data were extracted from a database. Because we only wished to assess the mean temperature over each species range, the coarse grid size of 25–50 km was adequate, given that the maps are based on a European extent and the distribution data are coarse. For the bird dataset, which included migratory species, we calculated temperature preference as the breeding temperature preference using average temperature data for April, May and June and the range maps restricted to breeding and/or resident areas.

Temperature preference was summarized for all species as the mean temperature across the range (mean of all occupied cells, weighted by grid cell coverage for range maps and removing duplicate records within the same cell for point occurrence data). We did further consider a more complex approach, fitting unimodal species response curves to identify species optimum temperatures. This led to temperature values that were correlated with the mean temperatures across species' ranges; however, since it also led to extreme estimates in a few cases (Supplementary Fig. 11), we decided to continue with our original simpler approach that made fewer assumptions about the shape of species responses.

We also calculated species' temperature ranges as the difference between the maximum and minimum temperature preference (mean of the five occupied grid cells with the warmest and coolest average temperature, respectively). Range size was estimated as the number of climatic grid cells intersecting with each species' distribution (because this was usually correlated with temperature range, we focused on temperature range instead, except for marine organisms, where we considered it as a proxy of habitat breadth). Because of the limited freely available occurrence data for freshwater plankton, temperature preference was approximated using the seasonal, rather than spatial pattern of species occurrences, within the population dataset, using a similar approach, with daily water temperature data.

**Additional species attributes.** Additional species attributes (for example, on habitat preference, dispersal ability and age at maturity) were obtained from the literature or databases in most cases (see Supplementary Table 3 for resources). For attribute data that had been fuzzy coded (for example, species given affinities to different levels associated with the attribute), we produced one attribute value by taking a weighted average of the affinities to different classes of the attribute when the underlying attribute was continuous (for example, size) or instead used cluster analysis to allocate each species to a single group. Habitat preferences for springtails and myriapods were inferred from the occurrence records that included information on habitat for each occurrence. Habitat breadth was calculated as the coefficient of variation of species affinities to different habitat categories[42]. In some cases, expert assessment was used to compile species attribute data (these are annotated in Supplementary Table 3). When species attribute data were ordinal, but represented a continuous variable, data were treated as continuous if there were at least five categories and graphical exploration suggested a linear relationship was reasonable. The few species that were not listed in the main attribute database were excluded from the analysis. Remaining missing attribute data were imputed using a random forest model, including all the variables of the subsequent regression models and the first eigenvector of the decomposed phylogenic/taxonomic tree as predictors[43]. The amount of missing data was generally less than 10% in most cases. However, for freshwater benthic invertebrates, only genus-level data were available for many attributes and even then up to 25% of data were missing for some attributes. The variable with the most missing data was pollution-related attributes (water-quality flexibility was only available for 50% of fish in one dataset).

**Local temperature data at the study sites.** Mean monthly temperature data were extracted for the study areas of all datasets. We used high-resolution data (in contrast to the large-scale coarse temperature data used for the species temperature preference calculation, see 'Additional species attributes') to retrieve temperature data at the very specific sites of population data sampling. Air temperatures for the terrestrial datasets were sourced from national weather service agencies (Deutsche Wetterdienst for Germany, www.dwd.se; Royal Meteorological Institute of Belgium for Belgium, www.meteo.be; and the European Climate Assessment and Dataset, http://www.ecad.eu, and local weather stations, http://www.weerstation-eelde.nl, for the Netherlands). For all but one of the marine realm datasets, water temperature data were sourced from the International Council for the Exploration of the Sea (ICES); for the remaining dataset, temperature data had been collected locally by the population dataset owner. Missing data were imputed using a generalized additive model. For the freshwater datasets, we used air temperature data when water temperature had not been collected (for the freshwater river fish and benthic invertebrates). These data were used to calculate annual averages of

daily mean temperatures. We smoothed the time series as a three-point lagged moving average and fitted a generalized least-square model to estimate the trend.

**Regression of species attributes on population trends.** For each dataset, multiple regression models were built to predict species' population trends using species attributes as predictors (that is, explanatory variables). We checked whether predictor variables were correlated before model fitting and also examined variance inflation factors of the fitted models to check for multicollinearity. We combined as many attributes as possible but always allowed for at least five species per model parameter. Because analysis was more often limited by the number of species than the number of attributes, we first identified the attributes that would probably be most important based on simple regressions and only included the most important (that is, lowest $P$ value) in the maximum multiple regression model. From this model, we excluded variables that were not significant in a stepwise manner. Coefficients of interest (temperature, habitat and pollution/nutrient preference/tolerance) that were not retained after model simplification were tested separately by adding them to the final simplified regression model. Rather than making a binary distinction between a significant or non-significant population trend, we used data from all species but weighted them by the precision (that is, inverse variance) of their trend estimate in the regression. This means that data points (that is, species) with a small standard error (that is, with more confidence, whether in a negative, stable or positive trend) had a greater weight in the model. Because highly fluctuating species (with low precision of the trend estimate) are more likely to be rare species, we additionally tested the results at two different thresholds of species inclusion, as well as with and without these weights (see Supplementary Figs 6 and 10). In addition, we used robust regression for our analysis to down-weight any influential species with high leverage[44].

As a sensitivity analysis of the accuracy of our temperature preference estimation, we also condensed our continuous temperature preference variable into a three-level factor (cold, average and warm temperature preference) and reran the analysis (see Supplementary Fig. 9). The conclusions were unaffected by this sensitivity analysis. Because our estimates of the temperature preferences of freshwater organisms were based on air temperature data, we also used stream zonation preferences as a measure of species' temperature preferences[45]; the results did not change (Supplementary Table 3). Analysis of species population trends fitted at the site-level within each dataset did not reveal any further habitat effects (see Supplementary Fig. 12).

**Phylogeny.** As species within each dataset do not necessarily provide independent data points due to shared ancestry, we tested whether phylogeny or taxonomy explained any variation in the residuals of our models and accounted for this in the few cases it did (see Supplementary Methods). Phylogenies with branch lengths were obtained for the birds[46] (using Beast[47] to produce a maximum credibility clade tree from the tree distribution), bats[48] and plants[49]. For the butterflies, we used an undated phylogeny from a molecular phylogenetic maximum likelihood analysis of the genes cytochrome $c$ oxidase I and elongation factor 1 alpha (M. Wiemers and O. Schweiger, unpublished observations). For the rest, we obtained the species taxonomic classification (mostly from the catalogue of life, except for the springtails[50] and phytoplankton[51]) and used the taxonomy to create a tree, setting branch lengths to one for each taxonomic rank. To check whether there was a phylogenetic signal in the residuals of the multiple regression models of population trends, we used Abouheif's $C_{mean}$ test[52] using the R package adephylo[53]. In most cases, there was no evidence that phylogeny or taxonomy explained any residual variation in the final simplified multiple regression models. In cases when it did (marine fish, springtails, beetles and bats), we specified a corPagel correlation structure using the R package ape[54] and reran the analysis as a generalized least-squares model.

**Effect size calculation.** The $t$-statistics of the model coefficients from the regression for each dataset were converted into correlation coefficients[55], which we used as a comparable effect size across all taxa and different species attributes. For categorical variables with multiple levels, we used the $t$-statistic of whichever pair-wise comparison was the largest. The $t$-statistics, and associated degrees of freedom (df), were converted into $r$, the correlation coefficient, using the following formulas[55].

For continuous variables, we calculated $r$ as:

$$r = \frac{t}{\sqrt{t^2 + \mathrm{df}}}$$

For categorical data, we initially used the $t$-statistic to calculate Cohen's $d$ as:

$$d = \frac{t(n_1 + n_2)}{\sqrt{n_1 n_2}\sqrt{\mathrm{df}}}$$

where $n_1$ and $n_2$ are the numbers of species in each group being compared. In cases when the categorical variable had multiple levels, we used the pair-wise contrast with the largest difference. For categorical variables that did not have any natural direction of effect (for example, habitat preference for birds, coded as forest, urban, farmland and wetland), the direction of effect was assigned according

to predictions relating to the associated environmental driver (for example, farmland birds were predicted to have the lowest trends, due to agricultural intensification). For comparability with other effect sizes, Cohen's $d$ was subsequently converted to $r$ as:

$$r = \frac{d}{\sqrt{d^2 + \frac{(n_1 + n_2)^2}{n_1 n_2}}}$$

For meta-analysis, $r$ was $z$-transformed and its standard error (s.e.$_{Zr}$) calculated as:

$$Zr = 0.5\ln\left[\frac{(1 + r)}{(1 - r)}\right]$$

$$\mathrm{s.e.}_{Zr} = \frac{1}{\sqrt{n - 3}}$$

**Meta-analysis.** Effect sizes ($z$-transformed correlation coefficients) from each dataset were combined using a random-effects meta-analysis[56] and the resulting pooled estimate and confidence intervals were back-transformed from Zr to $r$ for presentation. Statistical significance was assessed by whether the 95% confidence intervals of the effect sizes overlapped zero. Because there was some variation in the datasets, variables such as the start year of data collection, sampling sites and species number were centred and tested in the meta-analysis (Supplementary Table 4). The corrected effects of average temperature preference effects for each realm were produced by predicting the coefficients for each realm at the average value of all dataset-level variables across all datasets. Because there was overlap (taxonomic/spatial) among some of the datasets, we tested whether additional random terms that reflected dataset grouping could explain any variation; since they did not, they were removed. We also tested whether species in the upper and lower quantiles of temperature preference had average population trends that differed from zero using the $t$-statistic of the intercept term from a robust regression of the trends for each quartile and dataset. We then averaged the trends for each quartile and realm using a random-effects meta-analysis (sample sizes for each quantile and dataset are found in Supplementary Fig. 7). All analyses were conducted with R v3.0.2[57].

**Data availability.** As much as possible, references that include data owner contacts for each population dataset are given in Supplementary Table 1. Further information and data on species' local population trends are available from the corresponding author.

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## Author contributions

D.E.B. performed the analysis and wrote the outline of the paper with K.B.G. The study and analysis was perceived and designed by D.E.B., C.H., P.H., I.Kr., O.S. and K.B.G. All remaining authors contributed data towards the analysis. All authors helped draft the manuscript.

## Additional information

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## Competing interests

The authors declare no competing financial interests.

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# Cross-realm assessment of climate change impacts on species' abundance trends

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## Supplementary figures



**(a) Population data**: Temporal population data sets of communities

↓

**Prior subsetting**: Subset each to species seen in 25% of census years and check their taxonomy and synonyms

**Other species attributes**: literature and databases

**(b) Species attribute**: Estimate temperature preference from species distributions

**(c) Population trends**: Calculate a population trend for each species in each dataset (ar1 model using INLA)

Impute missing data if needed using a random forest model of the variables

**(d) Regression**: Analysis of species attributes (incl. temperature preference) versus population trends

If insufficient data points to include all attributes in one multiple regression model, use simple regressions to identify most significant attribute to enter the multiple regression

Multiple regression

**(e) Phylogeny**: Check whether taxonomy/phylogeny explains residual variation in a generalized least squares model

**Effect sizes**: Convert all effect sizes from regressions of dataset-level analyses into correlation coefficients

↓

**(f) Meta-analysis**: Combine correlation coefficients across datasets

*Data set-level analysis*

*Meta-analysis*

**Supplementary Fig. 1** Methods outline: the basic approach we took to analyze each dataset and combine the dataset-level analyses into a meta-analysis.
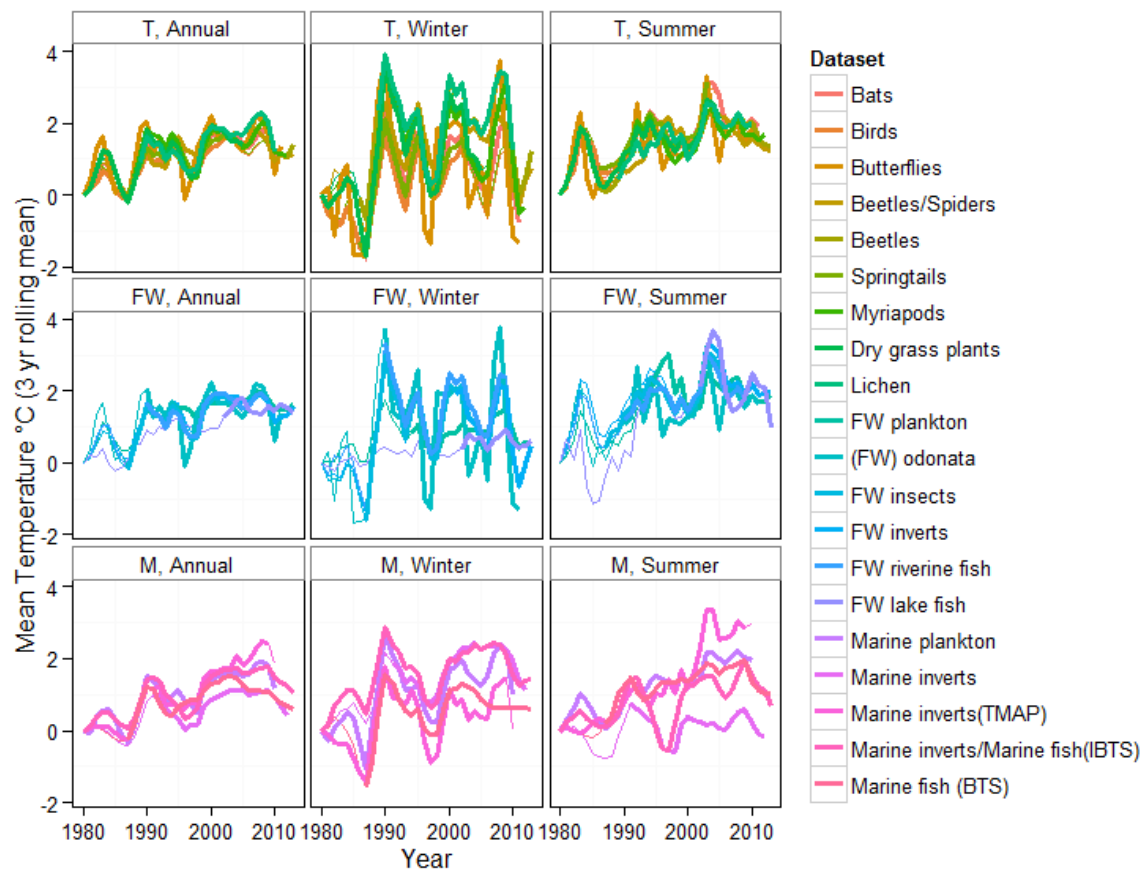
**Supplementary Fig. 2** Time series of average (annual, winter and summer) temperatures for each dataset. The line is thicker over the period of data collection for each dataset. T = terrestrial; FW = freshwater; M = marine. To facilitate comparison, all are set to 0 in 1980.
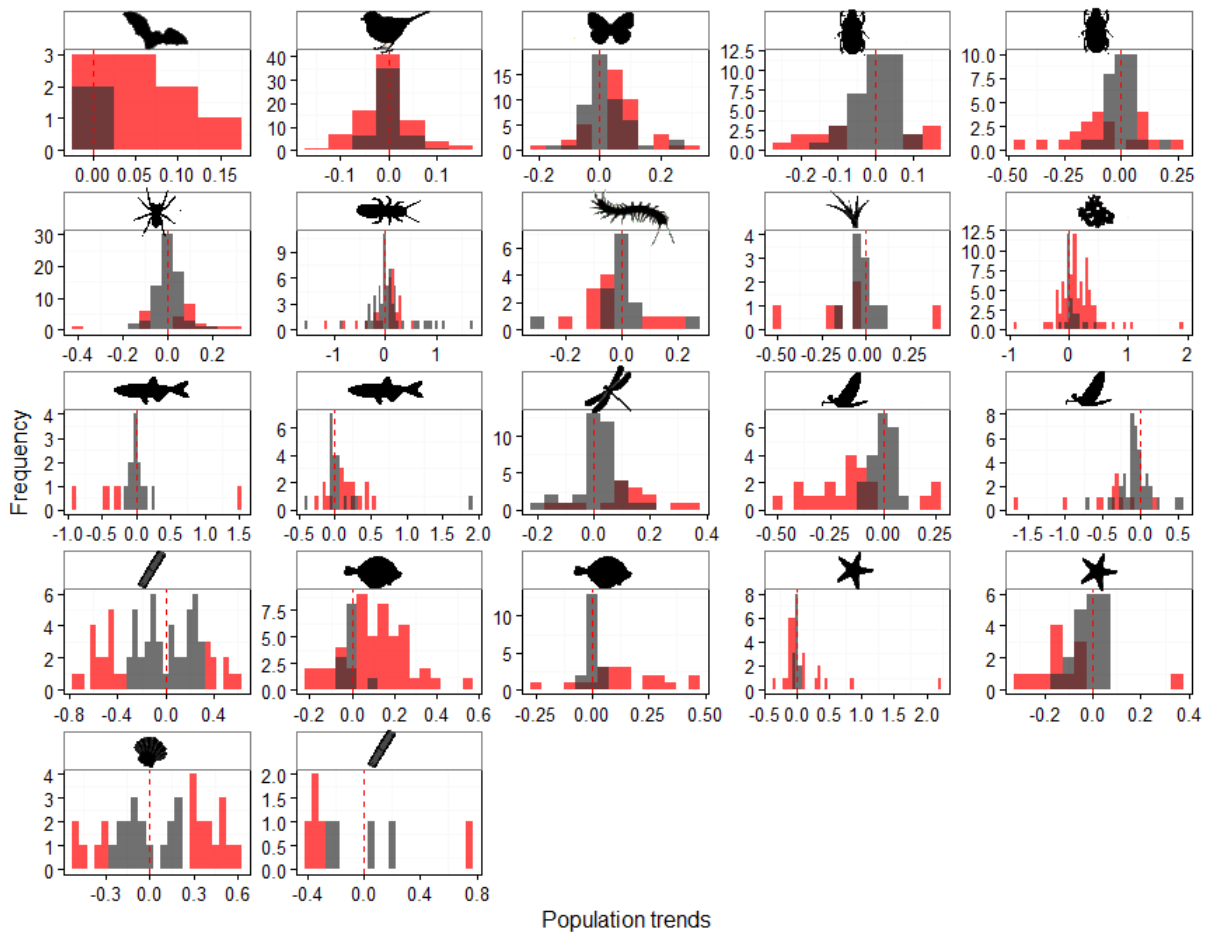
**Supplementary Fig. 3** Histograms of the population trends in each data set. The vertical dashed "zero line" indicates a stable population while positive and negative trends are to the right and left of the respectively. Red colouration indicating significant trends and grey colouration indicating non-significant trends. Trends were regarded as significant when their confidence intervals did not overlap zero, or, in the case of birds, when the direction of change was the same between each decadal census. Icons from left to right, top to bottom, refer to: bats, birds, butterflies, ground beetles x2, spiders, springtails, myriapods, dry grassland plants, lichen, lake fish, riverine fish, dragonflies, freshwater invertebrates x2, freshwater phytoplankton, marine fish x2, marine benthic invertebrates x3 and marine phytoplankton (presented in same order as rows in Supplementary Table 1).
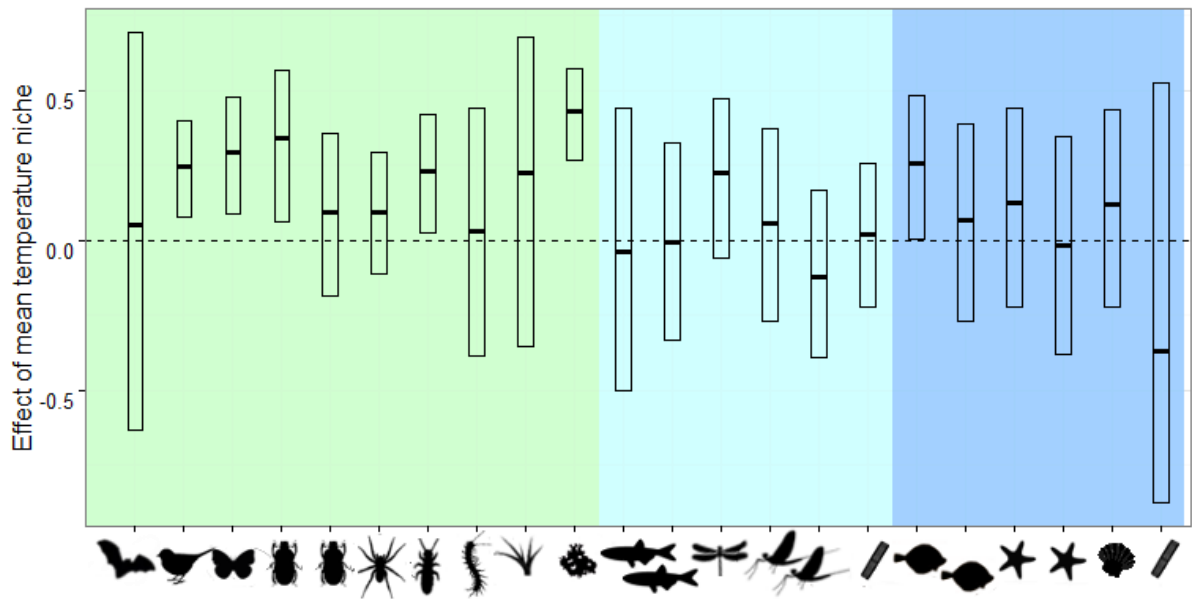
**Supplementary Fig. 4** Effect size (correlation coefficient, r, plus 95% confidence intervals) of the temperature preference on population trends. Colors refers to the realm of the dataset (green = terrestrial; light blue = freshwater; dark blue = marine). Icons from left to right refer to: bats, birds, butterflies, ground beetles x2, spiders, springtails, myriapods, dry grassland plants, lichen, lake fish, riverine fish, dragonflies, freshwater invertebrates x2, freshwater phytoplankton, marine fish x2, marine benthic invertebrates x3 and marine phytoplankton (presented in same order as rows in Table S1)
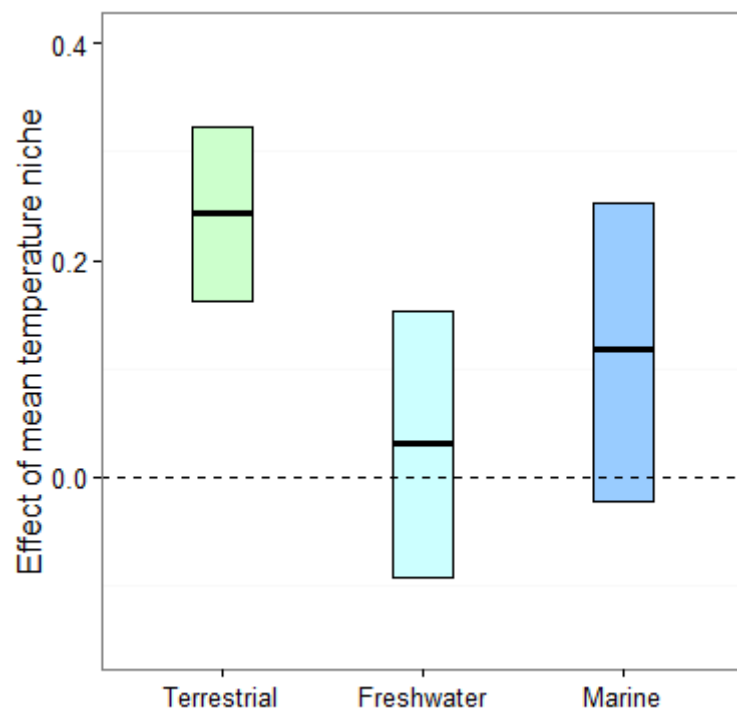
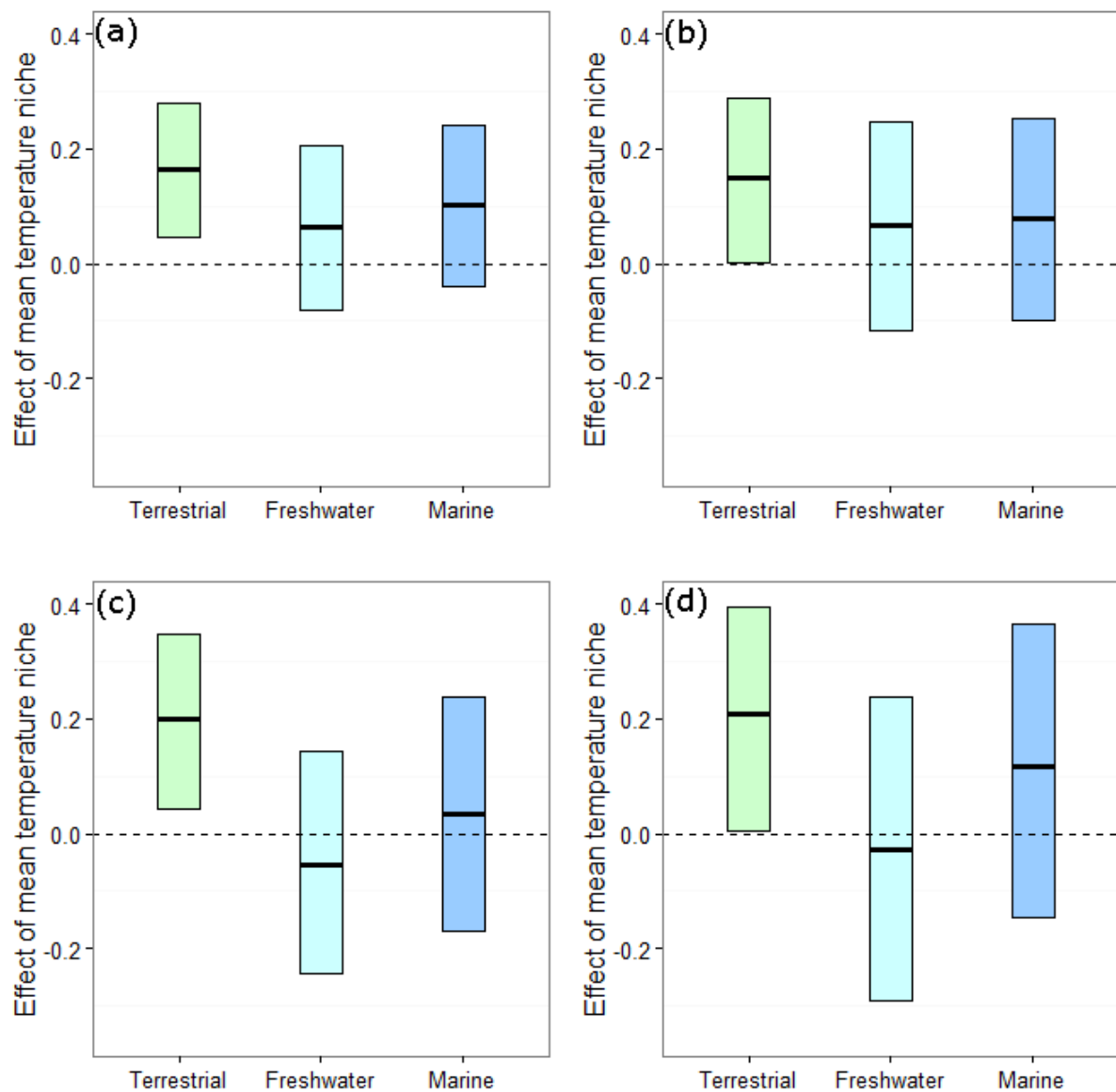**Supplementary Fig. 5** The average effect size (correlation coefficient, r, plus 95% confidence intervals) of the effect of temperature preference on population trends in each environmental realm without any correction for dataset-level characteristics.

**Supplementary Fig. 6** Sensitivity analysis of the effect of weighting and species threshold for inclusion on the results of Fig. 2b. Left graphs (a and c) are weighted; right graphs (b and d) are unweighted. Top graphs (a and b) are using species seen in at least 25% of census years; bottom graphs (c and d) are using species with a higher threshold (mean abundance of at least 5, or species seen in 75% of census years – for data available as standardized counts). Realm effect sizes are predicted at the average (log) number of species, (log) sampling sites and start year of all datasets.
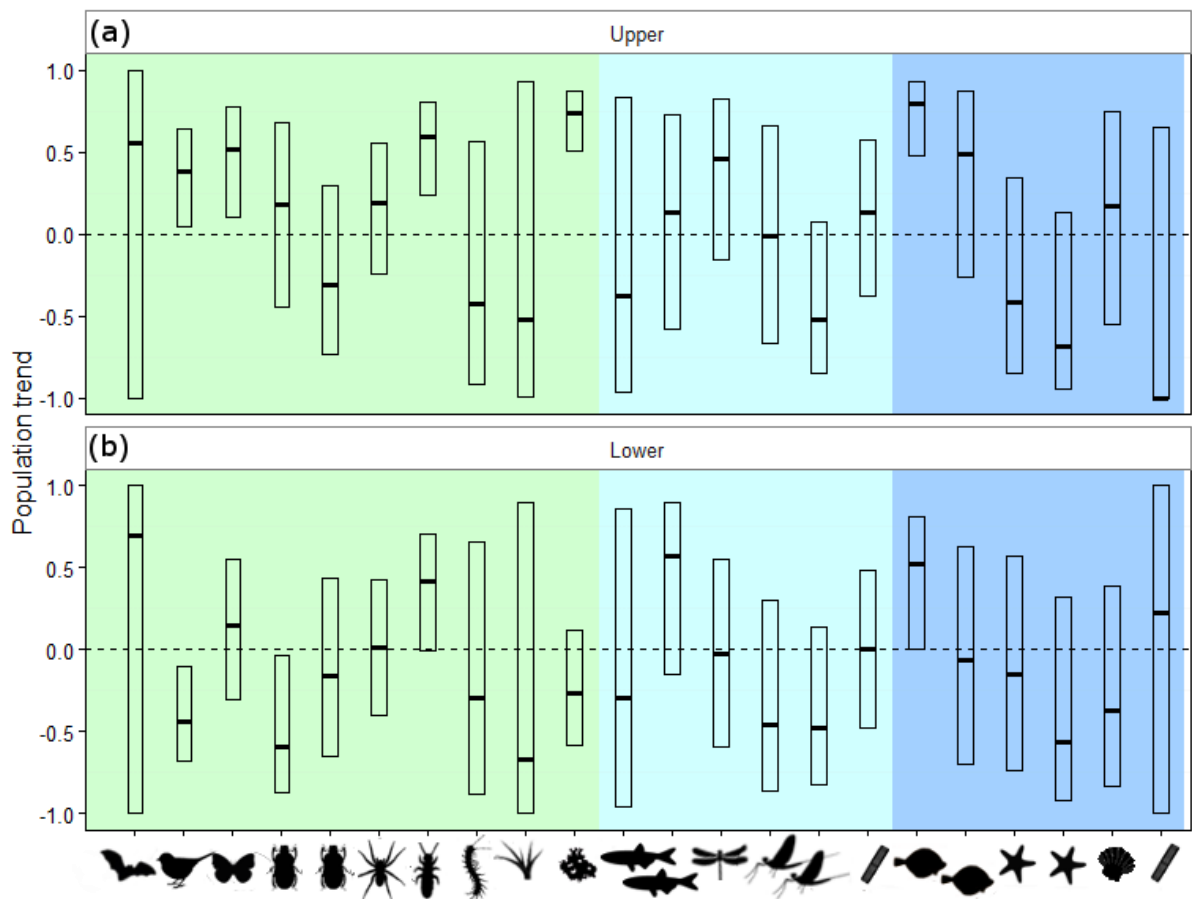
**Supplementary Fig. 7** The average (and 95% CI) population trends of species in the upper (a) and lower (b) quartiles of temperature preference in each dataset (left to right – green = terrestrial; light blue = freshwater, dark blue = marine). In this graph, population trends are presented as a directly comparable effect size across taxa: the correlation-coefficient of change in abundance/density with year (calculated from the t-statistic of the difference in trend from zero, converted to the correlation coefficient using formula given in the methods). Taxon symbols same as in Supplementary Fig. 4. Sample sizes in each quartile for each data set from left to right were 9, 33, 21, 12, 13, 23, 23, 6, 3 and 28 for terrestrial; 4, 9, 12, 9, 12 and 17 for freshwater and 15, 9, 9, 7, 9 and 2 for marine.
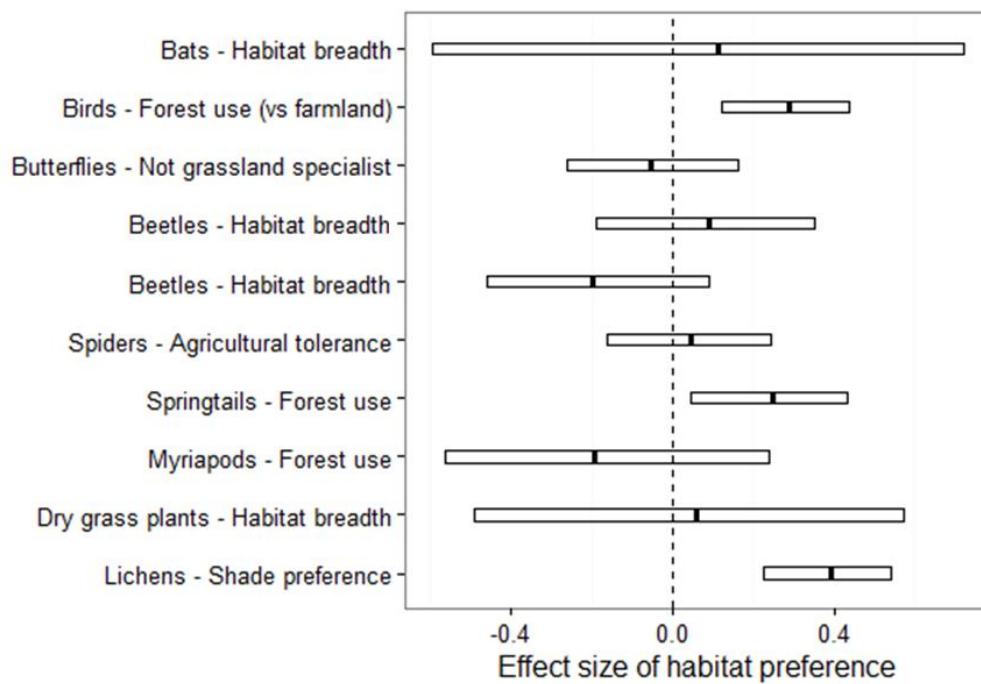
**Supplementary Fig. 8** The effect size of the "best" (i.e., largest absolute t-statistic when predicting population trends) habitat-related attributes for the terrestrial datasets. We expected decreases in habitat specialists, and increases of species preferring forest, and those tolerating agricultural land. Because in most cases, we tested more than one habitat variable per dataset (e.g., for beetles, we tested habitat breadth (generalists vs specialists) as well as tolerance of fertilized land), we took forward in the meta-analysis whichever had the largest absolute effect size in each case.
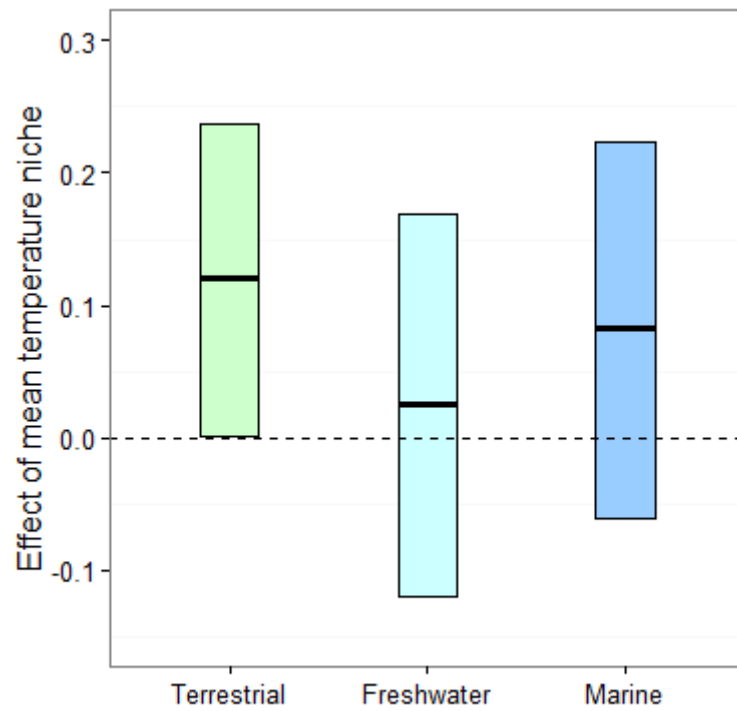
**Supplementary Fig. 9** The average effect size (correlation coefficient, r, plus 95% confidence intervals) of the difference between the population trends of warm-dwelling species (upper tertile of temperature preference) and cold-dwelling species (lower tertile) in each environmental realm without any correction for dataset-level characteristics.
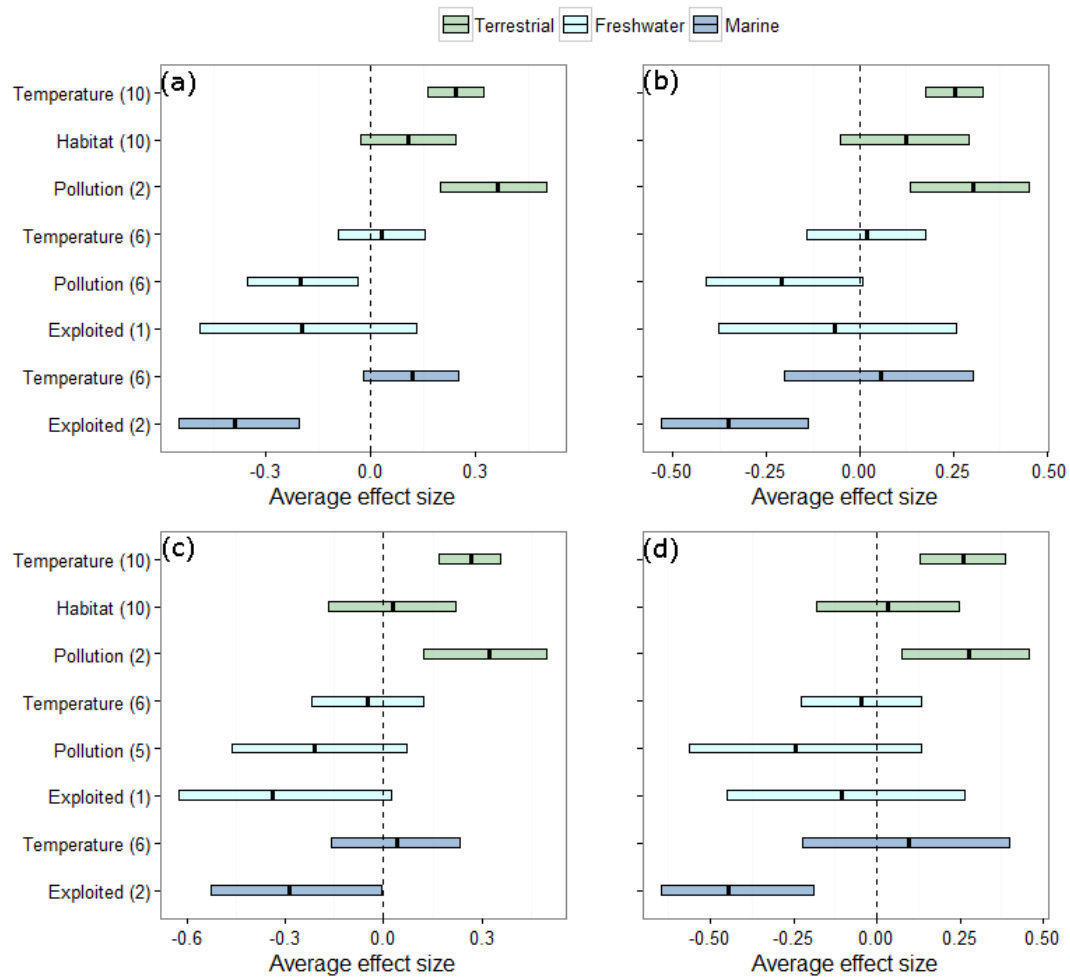
**Supplementary Fig. 10** Sensitivity analysis of the effect of weighting and species threshold for inclusion on the results of Fig. 3. Left graphs (a and c) are weighted; right graphs (b and d) are unweighted. Top graphs (a and b) are using species seen in at least 25% of census years; bottom graphs (c and d) are using species with a higher threshold (mean abundance of at least 5, or species seen in 75% of census years – for data available as standardized counts).
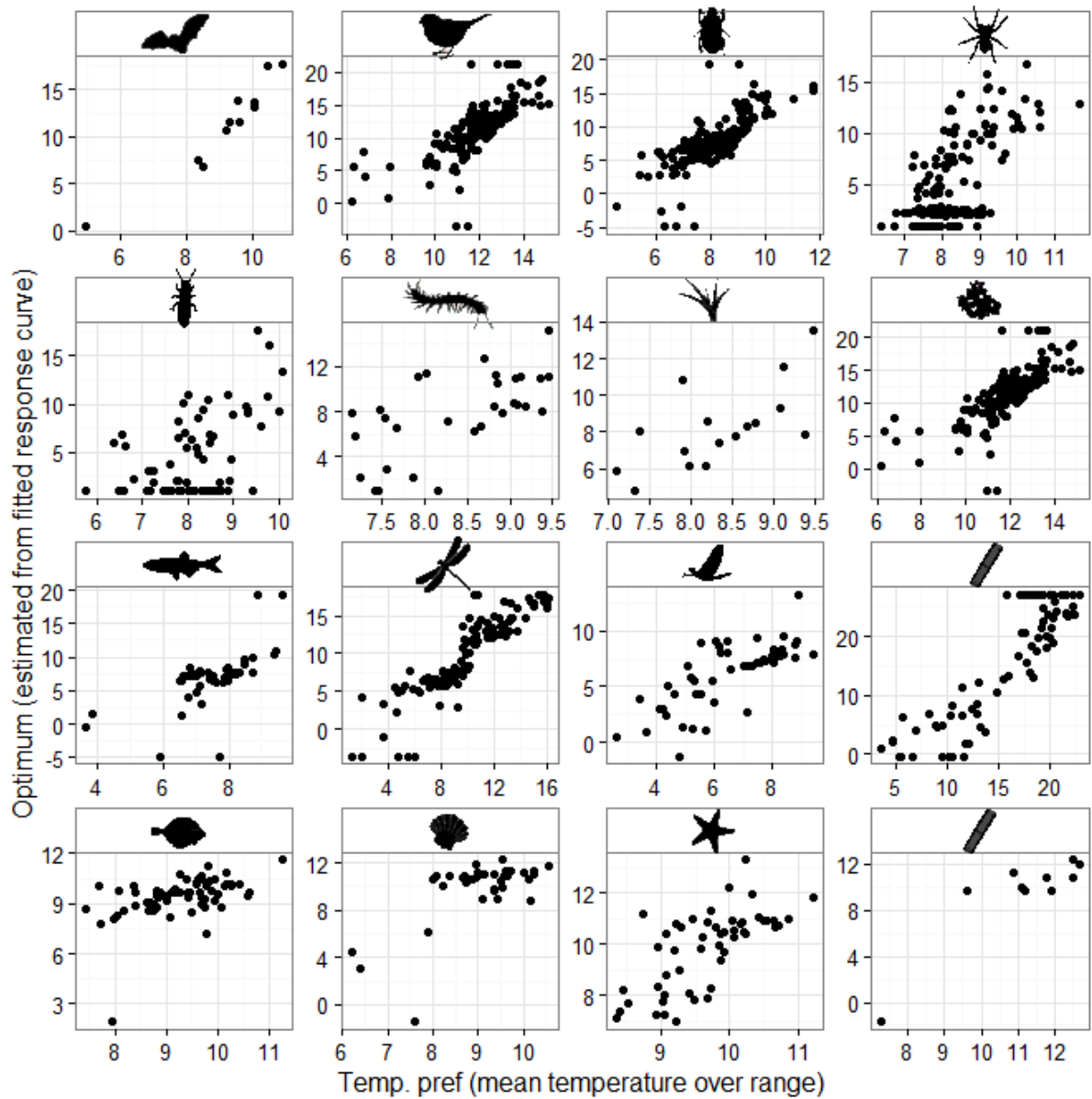
**Supplementary Fig. 11** The relationship between species' temperature preferences (as estimated as the mean over the European geographic range) and their estimated optimum temperature preferences (as estimated by fitting unimodal species' response curves to the same data using the eHOF package[1]). Butterflies are not included because their temperature preferences were extracted from the CLIMBER database[2].
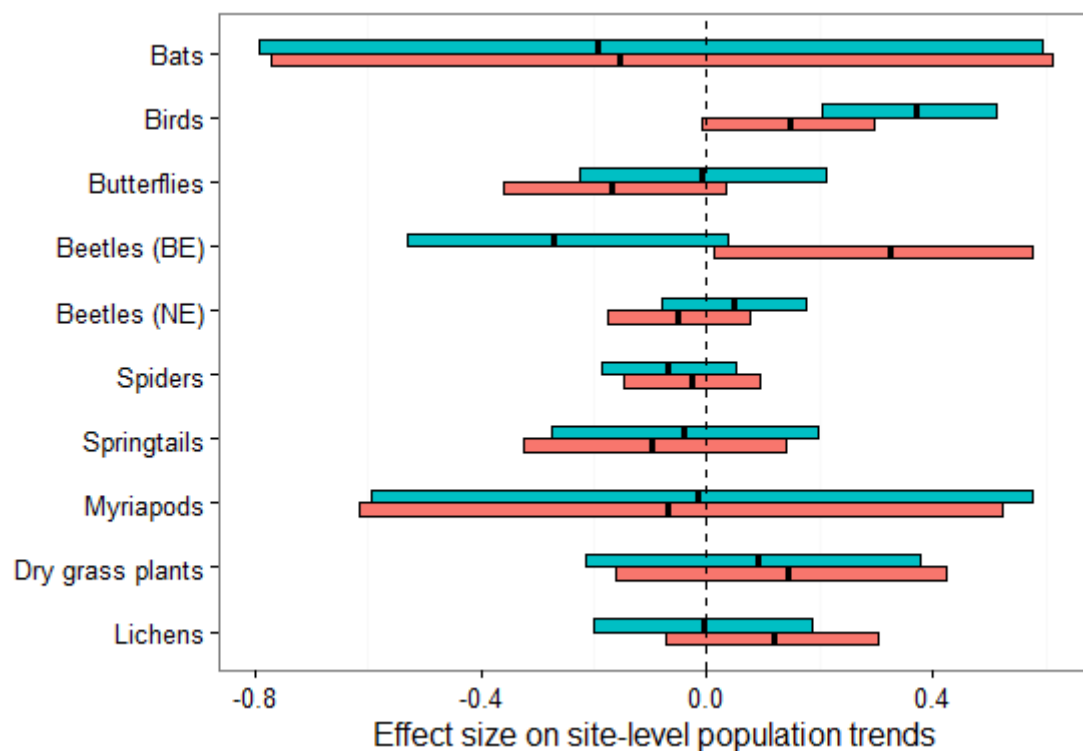
**Supplementary Fig. 12** Effect sizes of habitat preference (blue bars) and temperature preferences (red bars) on site-level species' population trends. Effect sizes were obtained from mixed models with site-level population trends (estimated in the same way as shown in Supplementary Fig. 1) as the response and species attributes as the predictors (temperature and habitat preference). Species and site were included as random factors. Shown are means ± 95% confidence intervals of the effect sizes (the correlation coefficient, r) calculated from the t-statistics of the model. We find that effects are weaker at the smaller spatial scales of the sites, which can be explained by smaller sample sizes at the site-level meaning less species trait diversity. This reduces the sensitivity of our analysis because our analysis rests on there being variation in species traits (or attributes) to relate to species' population trends. Habitat refers to the same variables as those shown for each taxa in Supplementary Fig. 8.

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Supplementary information for:

Cross-realm assessment of climate-change impacts on species' abundance trends – Bowler et al.

**Supplementary Table 1** Attributes of the datasets included in the meta-analysis

| Taxa | Start Year | Time Span | Census Years | Study Sites | Site area | Species | Method | Sampling frequency | Region | Further details |
|------|-----------|-----------|--------------|-------------|-----------|---------|--------|--------------------|--------|-----------------|
| Bats | 1990 | 22 | 22 | 310 | Winter roosts (caves, cellars, mines) | 11 | Usually one count was made per winter by trained surveyors for the Bayerisches Landesamt für Umwelt | Winter | Bavaria, DEU | Data were restricted to the most visited roosts. For more information on the data see Meschede and Rudolph[1] |
| Birds | 1980 | 23 | 8 | 303 | 2 x 2km | 133 | Transect counts collected by the Ornithologische Arbeitsgemeinschaft Bodensee | Breeding season | Lake Constance, DEU/CHE/AUT | Regional population data and population trends for each decadal census were obtained in the same way as previous analysis[2] |
| Butterflies | 1980 | 32 | 32 | 184 | c. 10 x 10 km | 88 | Observations made by entomologists and compiled by the Sächsisches | All year | Saxony, DEU | To maximize use of this sparse dataset, we used data from all grid cells. Data were |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Landesamt für Umwelt, Landwirtschaft und Geologie | | | restricted to May to September and month included as a fixed factor. Total monthly records was included as an offset "effort" term. |
| Ground beetles (Belgium) | 1990 | 17 | 17 | 3 | 3 traps at each site separated by 2 m | 50 | Pitfall traps | All year | Ijzermonding, BEL | Traps were checked biweekly. Data shared on annual totals. |
| Ground beetles (Netherlands) | 1986 | 28 | 22 | 5 | 3 traps at each site separated by 10 m | 54 | Pitfall traps | All year | Dwingelder Veld, NLD | Traps were checked biweekly during most of the year. Data were restricted to the most monitored series[3]. |
| Spiders | 1990 | 24 | 24 | 3 | 3 traps at each site separated by 2 m | 96 | Pitfall traps | All year | Ijzermonding, BEL | Traps were checked biweekly. Data shared on annual totals. |
| Springtails | 1986 | 18 | 8 | 56 | 5 x 5 m | 93 | Soil core sampling for the Landesanstalt für Umwelt, Messungen und Naturschutz | Spring, summer, autumn | Baden Württemberg, DEU | Data shared on total per sampling season. |

| | | | | | | | | | Baden-Württemberg | |
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| Myriapods | 1988 | 25 | 4 | 3 | 5 to 10 traps per site | 25 | Pitfall traps | Spring, Autumn | Görlitz, DEU | For consistency, we focused on data collected in April/May and September/October. We used species seen in at least 2 years. |
| Dry grass plants | 1980 | 25 | 22 | 3 | 1 x 1m | 16 | Vegetation survey | late Spring | Halle, DEU | Data used on number of individuals of each plant[4] |
| Lichens | 1989 | 22 | 8 | 610 | Usually 10 trees | 114 | Tree surveys | All year | Drenthe, NLD | Lichen abundance asssessed on an 8-point scale, usually at four times over the study period per site[5] We used ordinal regression to estimate the long-term trend. |
| FW fish (lake) | 2002 | 12 | 12 | 3 | Beach seines (16 x1 m) hauled from 1 m depth of | 20 | Fishing | May to Sept | Lake Constance, DEU | 2 or 3 replicates each time, which was included as an offset term[6]. |

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| | | | | | shorelines | | | | | |
| FW fish (riverine) | 1990 | 20 | 20 | 7 | Median reach length 250 m | 38 | Electrofishing data collected by the German federal state agencies | All year | Hesse/ North Rhine-Westphalia (Hönne, Lenne, Lippe, Rhein, Ruhr, Rur, Sieg), DEU | Data were restricted to the most visited rivers. Length of reach sampled was included as an offset term. |
| Odonata | 1990 | 22 | 22 | 132 | c. 10 x 10 km | 52 | Observations made by entomologists and compiled by the Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie | All year | Saxony, DEU | To maximize use of this sparse dataset, we used data from all grid cells. Data were restricted to May to September and month included as a fixed factor. Total monthly records was included as an offset "effort" term. |
| FW inverts (Breitenbach) | 1987 | 19 | 19 | 1 | 12 m long greenhouse over stream | 40 | Net catch | All year (daily retrieval of emerging adults) | Breitenbach, DEU | For more information on the data, see Wagner et al.[7.] |
| FW inverts (Aubach/Bieb | 2001 | 13 | 12 | 2 | 25 m$^2$ | 51* | Water sampling (Modified | March, April | Aubach/Bieber, DEU | For more information on the |

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| er) | | | | | AQEM/STAR protocol) | | | | | sampling, see Haase et al.[8] |
| FW phytoplankton | 1994 | 20 | 20 | 1 | 5-l Friedinger sampler | 70* | Water sampling | All year (monday sampling) | Müggelsee, DEU | Data provided as mg/L[9]. Population trends estimated as Kendall τ. |
| Marine fish (NS-IBTS) | 1980 | 34 | 30 | 24 | GOV gear with haul duration usually 30 min at 4 knots | 61 | Trawling (North-Sea International Bottom Trawl Survey) | 1st quarter (Jan to March) | southern North Sea | Data were restricted to southern ICES rectangles that overlap with the above benthos dataset in south North Sea. Haul duration was included as an offset term[10] |
| Marine fish (BTS) | 1987 | 27 | 27 | 7 | BT8 gear with haul duration usually 30 min at 4 knots | 39 | Trawling (Netherlands Bottom Trawl Survey) | August (20 survey days) | southern North Sea | Data were restricted to ICES rectangles off the Netherlands coast, not overlapping with above dataset. Haul duration was included as an offset term[11] |
| Marine inverts (Dogger bank) | 1991 | 22 | 19 | 37 | 2-m beam trawl towed for 1 nautical | 37 | Trawling | Summer | Dogger Bank, North Sea | For more information on the data, see Sonnewald and |

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| | | | | | mile | | | | | Türkay[12]. |
| Marine inverts (south North Sea) | 1998 | 15 | 13 | 24 | 2-m beam trawl towed at a speed of 1.5–2 knots for 5 min | 32* | Trawling | Summer | southern North Sea | For more information on the data, see Neumann et al.[13]. |
| Marine infauna (TMAP) | 1980 | 30 | 30 | 39 | Each sample was recommended to cover 400–4500 cm$^2$ | 37 | Benthic core sampling | Once/twice per year, spring /summer | Wadden Sea, North Sea | Standardized count data provided[14] – population trends estimated as Kendall τ. |
| Marine phytoplankton | 1980 | 31 | 31 | 1 | Surface water sample | 9 | Water sampling using the Utermöhl method, 25 or 50 ml of the water sample is counted daily to species level | All year | Helgolands, DEU | Data provided as cells/L[15]. Population trends estimated as Kendall τ. |

*a small number of "species" are genera (see Table S2)

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Supplementary information for:

Cross-realm assessment of climate-change impacts on species' abundance trends

– Bowler et al.

**Supplementary Table 2**. Species used for population analysis within each dataset (species observed in 25% of census years)

| Taxa | Species |
|------|---------|
| Bats | Barbastella barbastellus, Eptesicus nilssonii, Eptesicus serotinus, Myotis bechsteinii, Myotis daubentonii, Myotis myotis, Myotis nattereri, Plecotus auritus, Plecotus austriacus, Rhinolophus ferrumequinum, Rhinolophus hipposideros |
| Birds | Accipiter gentilis, Accipiter nisus, Acrocephalus arundinaceus, Acrocephalus palustris, Acrocephalus scirpaceus, Actitis hypoleucos, Aegithalos caudatus, Alauda arvensis, Alcedo atthis, Anas clypeata, Anas crecca, Anas platyrhynchos, Anas querquedula, Anas strepera, Anthus trivialis, Apus apus, Ardea cinerea, Asio otus, Athene noctua, Aythya ferina, Aythya fuligula, Buteo buteo, Carduelis cannabina, Carduelis carduelis, Carduelis chloris, Carduelis flammea, Carduelis spinus, Certhia brachydactyla, Certhia familiaris, Charadrius dubius, Cinclus cinclus, Circus aeruginosus, Coccothraustes coccothraustes, Columba livia, Columba oenas, Columba palumbus, Corvus corax, Corvus corone, Corvus monedula, Coturnix coturnix, Cuculus canorus, Cygnus olor, Delichon urbicum, Dendrocopos major, Dendrocopos medius, Dendrocopos minor, Dryocopus martius, Emberiza cirlus, Emberiza citrinella, Emberiza schoeniclus, Erithacus rubecula, Falco subbuteo, Falco tinnunculus, Ficedula hypoleuca, Fringilla coelebs, Fulica atra, Gallinago gallinago, Gallinula chloropus, Garrulus glandarius, Hippolais icterina, Hirundo rustica, Ixobrychus minutus, Jynx torquilla, Lanius collurio, Larus canus, Larus ridibundus, Limosa limosa, Locustella luscinioides, Locustella naevia, Loxia curvirostra, Lullula arborea, Luscinia megarhynchos, Miliaria calandra, Miliaria calandra, Milvus migrans, Milvus milvus, Motacilla alba, Motacilla cinerea, Motacilla flava, Muscicapa striata, Netta rufina, Nucifraga caryocatactes, Numenius arquata, Oriolus oriolus, Panurus biarmicus, Parus ater, Parus caeruleus, Parus cristatus, Parus major, Parus montanus, Parus palustris, Passer domesticus, Passer montanus, Perdix perdix, Pernis apivorus, Phoenicurus ochruros, Phoenicurus phoenicurus, Phylloscopus bonelli, Phylloscopus collybita, Phylloscopus sibilatrix, Phylloscopus trochilus, Pica pica, Picus canus, Picus viridis, Podiceps cristatus, Podiceps nigricollis, Porzana porzana, Prunella modularis, Pyrrhula pyrrhula, Rallus aquaticus, Regulus ignicapilla, Regulus regulus, Riparia riparia, Saxicola rubetra, Saxicola torquatus, Serinus serinus, Sitta europaea, Sterna hirundo, Streptopelia decaocto, Streptopelia turtur, Strix aluco, Sturnus vulgaris, Sylvia atricapilla, Sylvia borin, Sylvia communis, Sylvia curruca, Tachybaptus ruficollis, Troglodytes troglodytes, Turdus merula, Turdus philomelos, Turdus pilaris, Turdus viscivorus, Tyto alba, |

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| | Vanellus vanellus |
| Butterflies | Aglais io, Aglais urticae, Anthocharis cardamines, Apatura ilia, Apatura iris, Aphantopus hyperantus, Aporia crataegi, Araschnia levana, Argynnis adippe, Argynnis aglaja, Argynnis niobe, Argynnis paphia, Aricia agestis, Boloria aquilonaris, Boloria dia, Boloria selene, Brenthis ino, Callophrys rubi, Carcharodus alceae, Carterocephalus palaemon, Celastrina argiolus, Coenonympha arcania, Coenonympha glycerion, Coenonympha pamphilus, Colias crocea, Colias hyale, Colias palaeno, Cupido minimus, Erebia ligea, Erebia medusa, Erynnis tages, Euphydryas aurinia, Euphydryas maturna, Favonius quercus, Gonepteryx rhamni, Hesperia comma, Heteropterus morpheus, Hipparchia hermione, Hipparchia semele, Hipparchia statilinus, Hyponephele lycaon, Iphiclides podalirius, Issoria lathonia, Lasiommata maera, Lasiommata megera, Leptidea sinapis, Limenitis populi, Lycaena alciphron, Lycaena dispar, Lycaena hippothoe, Lycaena phlaeas, Lycaena tityrus, Lycaena virgaureae, Maniola jurtina, Melanargia galathea, Melitaea athalia, Melitaea cinxia, Melitaea diamina, Nymphalis antiopa, Nymphalis c-album, Nymphalis polychloros, Ochlodes sylvanus, Papilio machaon, Pararge aegeria, Phengaris nausithous, Phengaris teleius, Pieris brassicae, Pieris napi, Pieris rapae, Plebejus argus, Plebejus idas, Plebejus optilete, Polyommatus amandus, Polyommatus coridon, Polyommatus icarus, Polyommatus semiargus, Pontia edusa, Pyrgus malvae, Pyronia tithonus, Satyrium pruni, Satyrium w-album, Scolitantides orion, Thecla betulae, Thymelicus acteon, Thymelicus lineola, Thymelicus sylvestris, Vanessa atalanta, Vanessa cardui |
| Ground beetles (Belgium) | Amara aenea, Amara apricaria, Amara aulica, Amara bifrons, Amara curta, Amara familiaris, Amara lucida, Amara similata, Amara spreta, Amara tibialis, Badister bullatus, Bembidion lunulatum, Bembidion minimum, Bembidion properans, Bembidion quadrimaculatum, Bradycellus harpalinus, Bradycellus verbasci, Calathus ambiguus, Calathus cinctus, Calathus erratus, Calathus fuscipes, Calathus melanocephalus, Calathus mollis, Demetrias atricapillus, Demetrias monostigma, Dyschirius angustatus, Harpalus affinis, Harpalus anxius, Harpalus pumilus, Harpalus rubripes, Harpalus servus, Harpalus tardus, Leistus ferrugineus, Leistus fulvibarbis, Licinus depressus, Masoreus wetterhallii, Microlestes maurus, Nebria brevicollis, Nebria salina, Notiophilus biguttatus, Notiophilus substriatus, Paradromius linearis, Philorhizus melanocephalus, Philorhizus notatus, Pseudoophonus rufipes, Pterostichus strenuus, Syntomus foveatus, Syntomus truncatellus, Trechus obtusus, Trechus quadristriatus |
| Ground beetles (Netherlands) | Agonum sexpunctatum, Amara aenea, Amara apricaria, Amara communis, Amara equestris, Amara familiaris, Amara fulva, Amara lunicollis, Amara plebeja, Anisodactylus binotatus, Bembidion lampros, Bembidion nigricorne, Bradycellus caucasicus, Bradycellus harpalinus, Bradycellus ruficollis, Broscus cephalotes, Calathus cinctus, Calathus erratus, Calathus fuscipes, Calathus melanocephalus, Carabus arvensis, Carabus granulatus, Carabus nemoralis, Carabus nitens, Carabus problematicus, Cicindela hybrida, Clivina fossor, Cymindis macularis, Harpalus affinis, Harpalus anxius, Harpalus distinguendus, Harpalus latus, Harpalus rubripes, Harpalus rufipalpis, Harpalus tardus, Leistus |

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| | terminatus, Limodromus assimilis, Loricera pilicornis, Masoreus wetterhallii, Nebria brevicollis, Nebria salina, Notiophilus aquaticus, Olisthopus rotundatus, Oxypselaphus obscurus, Poecilus cupreus, Poecilus lepidus, Poecilus versicolor, Pseudoophonus rufipes, Pterostichus diligens, Pterostichus melanarius, Pterostichus minor, Pterostichus niger, Pterostichus oblongopunctatus, Trichocellus cognatus |
| Spiders | Acartauchenius scurrilis, Agroeca cuprea, Agroeca lusatica, Agroeca proxima, Alopecosa barbipes, Alopecosa pulverulenta, Arctosa perita, Argenna subnigra, Baryphyma maritimum, Bathyphantes gracilis, Bathyphantes parvulus, Centromerita bicolor, Centromerita concinna, Centromerus prudens, Centromerus sylvaticus, Ceratinella brevipes, Cheiracanthium virescens, Cicurina cicur, Clubiona frisia, Clubiona subtilis, Collinsia inerrans, Dicymbium nigrum nigrum, Diplostyla concolor, Drassodes cupreus, Dysdera crocata, Enoplognatha thoracica, Entelecara erythropus, Erigone arctica, Erigone atra, Erigone dentipalpis, Erigone promiscua, Ero aphana, Ero furcata, Euophrys frontalis, Hahnia nava, Haplodrassus dalmatensis, Haplodrassus signifer, Maso sundevalli, Meioneta rurestris, Metopobactrus prominulus, Micaria dives, Micaria pulicaria, Neriene clathrata, Oedothorax apicatus, Oedothorax fuscus, Oedothorax retusus, Ostearius melanopygius, Ozyptila atomaria, Ozyptila praticola, Ozyptila sanctuaria, Ozyptila simplex, Pachygnatha degeeri, Palliduphantes ericaeus, Palliduphantes pallidus, Parapelecopsis nemoralioides, Pardosa monticola, Pardosa nigriceps, Pardosa palustris, Pardosa pullata, Pelecopsis parallela, Peponocranium ludicrum, Philodromus fallax, Phlegra fasciata, Pisaura mirabilis, Pocadicnemis juncea, Porrhomma microphthalmum, Prinerigone vagans, Robertus lividus, Sitticus distinguendus, Sitticus saltator, Stemonyphantes lineatus, Styloctetor romanus, Synageles venator, Tapinocyba praecox, Tegenaria agrestis, Tegenaria atrica, Tenuiphantes tenuis, Thanatus striatus, Tibellus maritimus, Tiso vagans, Trichopterna cito, Trochosa ruricola, Trochosa terricola, Troxochrus scabriculus, Typhochrestus digitatus, Walckenaeria acuminata, Walckenaeria antica, Walckenaeria atrotibialis, Walckenaeria monoceros, Walckenaeria stylifrons, Walckenaeria unicornis, Xysticus cristatus, Xysticus erraticus, Xysticus kochi, Zelotes electus, Zelotes longipes |
| Springtails | Allacma fusca, Anurida granulata, Arrhopalites caecus, Arrhopalites ornatus, Ceratophysella armata, Ceratophysella denticulata, Ceratophysella sigillata, Ceratophysella succinea, Choreutinula inermis, Coloburella reticulata, Cryptopygus thermophilus, Desoria propinqua, Desoria violacea, Deuteraphorura silvaria, Dicyrtoma fusca, Dicyrtomina ornata, Entomobrya corticalis, Entomobrya muscorum, Entomobrya nivalis, Entomobrya quinquelineata, Folsomia candida, Folsomia manolachei, Folsomia penicula, Folsomia quadrioculata, Folsomia spinosa, Folsomides parvulus, Friesea mirabilis, Heteromurus nitidus, Hymenaphorura sibirica, Hypogastrura purpurescens, Isotoma viridis, Isotomiella minor, Isotomiella paraminor, Isotomodes templetoni, Isotomurus palustris, Lepidocyrtus curvicollis, Lepidocyrtus cyaneus, Lepidocyrtus lanuginosus, Lepidocyrtus lignorum, Lipothrix lubbocki, Megalothorax minimus, Mesaphorura jarmilae, Mesaphorura krausbaueri, Mesaphorura macrochaeta, Micranurida forsslundi, Micranurida |

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| | pygmaea, Neanura muscorum, Neelides minutus, Neelus murinus, Neotullbergia tricuspis, Oligaphorura groenlandica, Oncopodura crassicornis, Onychiuroides granulosus, Onychiurus humatus, Orchesella flavescens, Orogastrura parva, Paratullbergia callipygos, Parisotoma notabilis, Pogonognathellus flavescens, Pogonognathellus longicornis, Proisotoma minima, Proisotoma minuta, Protaphorura armata, Protaphorura aurantiaca, Protaphorura campata, Protaphorura glebata, Protaphorura quadriocellata, Protaphorura subuliginata, Protaphorura tricampata, Pseudachorutes dubius, Pseudachorutes subcrassus, Pseudanurophorus binoculatus, Pseudisotoma sensibilis, Pseudosinella alba, Pseudosinella binoculata, Schoettella ununguiculata, Sminthurides parvulus, Sminthurides schoetti, Sminthurinus aureus, Sminthurinus niger, Sphaeridia pumilis, Stenaphorura denisi, Stenaphorura quadrispina, Stenognathellus denisi, Supraphorura furcifera, Tomocerus baudoti, Tomocerus minor, Tomocerus vulgaris, Willemia anophthalma, Willemia denisi, Xenylla brevicauda, Xenylla grisea, Xenylla tullbergi |
| Myriapods | Glomeris hexasticha, Julus scandinavius, Lithobius agilis, Lithobius austriacus, Lithobius dentatus, Lithobius erythrocephalus, Lithobius forficatus, Lithobius macilentus, Lithobius microps, Lithobius mutabilis, Lithobius nodulipes, Mastigona bosniense, Megaphyllum projectum kochi, Mycogona germanica, Ochogona caroli, Polydesmus complanatus, Polydesmus denticulatus, Polyzonium germanicum, Proteroiulus fuscus, Schendyla nemorensis, Strigamia acuminata, Strigamia crassipes, Strigamia transsilvanica, Strongylosoma stigmatosum, Unciger foetidus |
| Dry grass plants | Agrostis capillaris, Centaurea stoebe, Cerastium semidecandrum, Dianthus carthusianorum, Euphorbia cyparissias, Festuca glaucina, Hieracium pilosella, Hypericum perforatum, Hypochaeris radicata, Koeleria macrantha, Rumex acetosella, Scleranthus perennis, Silene otites, Spergula morisonii, Thymus serpyllum, Viola arvensis |
| Lichens | Amandinea punctata, Anaptychia ciliaris, Arthonia radiata, Arthonia spadicea, Bacidia chloroticula, Bacidia neosquamulosa, Buellia griseovirens, Calicium viride, Caloplaca citrina, Caloplaca herbidella, Candelaria concolor, Candelariella aurella, Candelariella reflexa, Candelariella vitellina, Candelariella xanthostigma, Catillaria nigroclavata, Chaenotheca chrysocephala, Chaenotheca ferruginea, Chaenotheca furfuracea, Chaenotheca trichialis, Chrysothrix candelaris, Cladonia caespiticia, Cladonia coniocraea, Cladonia digitata, Cladonia fimbriata, Cladonia glauca, Cladonia macilenta, Cliostomum griffithii, Dimerella pineti, Diploicia canescens, Evernia prunastri, Fellhanera bouteillei, Flavoparmelia caperata, Flavoparmelia soredians, Haematomma ochroleucum, Hyperphyscia adglutinata, Hypogymnia physodes, Hypogymnia tubulosa, Hypocenomyce scalaris, Lecanactis abietina, Lecania rabenhorstii, Lecanora argentata, Lecanora carpinea, Lecanora chlarotera, Lecanora conizaeoides, Lecanora dispersa, Lecanora expallens, Lecanora hagenii, Lecanora muralis, Lecanora pulicaris, Lecanora saligna, Lecanora symmicta, Lecanora varia, Lecidella elaeochroma, Lecidella scabra, Lecidella stigmatea, Lepraria incana, Lepraria lobificans, Leproloma vouauxii, Melanelia elegantula, Melanelia exasperatula, Melanelia fuliginosa, Melanelia laciniatula, Melanelia subaurifera, Micarea denigrata, Micarea prasina, Mycoblastus fucatus, |

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| | Ochrolechia androgyna, Ochrolechia microstictoides, Ochrolechia turneri, Opegrapha atra, Opegrapha rufescens, Opegrapha varia, Opegrapha vermicellifera, Parmelina tiliacea, Parmelia sulcata, Parmeliopsis ambigua, Parmotrema chinense, Pertusaria albescens, Pertusaria amara, Pertusaria coccodes, Pertusaria hemisphaerica, Pertusaria pertusa, Phaeophyscia nigricans, Phaeophyscia orbicularis, Phlyctis argena, Physcia adscendens, Physcia aipolia, Physcia caesia, Physcia dubia, Physcia stellaris, Physcia tenella, Physconia distorta, Physconia enteroxantha, Physconia grisea, Placynthiella icmalea, Platismatia glauca, Pleurosticta acetabulum, Protoparmelia hypotremella, Pseudevernia furfuracea, Punctelia borreri, Ramalina farinacea, Ramalina fastigiata, Ramalina fraxinea, Ramalina pollinaria, Rinodina pityrea, Schismatomma decolorans, Strangospora pinicola, Trapeliopsis flexuosa, Trapeliopsis granulosa, Tuckermannopsis chlorophylla, Xanthoria candelaria, Xanthoria parietina, Xanthoria polycarpa |
| FW fish (lake) | Abramis brama, Alburnus alburnus, Anguilla anguilla, Barbatula barbatula, Barbus barbus, Cottus gobio, Cyprinus carpio, Esox lucius, Gasterosteus aculeatus, Gobio gobio, Gymnocephalus cernua, Leucaspius delineatus, Leuciscus leuciscus, Lota lota, Perca fluviatilis, Rutilus rutilus, Sander lucioperca, Scardinius erythrophthalmus, Squalius cephalus, Tinca tinca |
| FW fish (riverine) | Abramis brama, Alburnoides bipunctatus, Alburnus alburnus, Anguilla anguilla, Aspius aspius, Barbatula barbatula, Barbus barbus, Blicca bjoerkna, Carassius carassius, Carassius gibelio, Chondrostoma nasus, Cobitis taenia, Cottus gobio, Cyprinus carpio, Esox lucius, Gasterosteus aculeatus, Gobio gobio, Gymnocephalus cernua, Lampetra fluviatilis, Lampetra planeri, Leucaspius delineatus, Leuciscus idus, Leuciscus leuciscus, Lota lota, Perca fluviatilis, Petromyzon marinus, Phoxinus phoxinus, Platichthys flesus, Pungitius pungitius, Rutilus rutilus, Salmo salar, Salmo trutta, Sander lucioperca, Scardinius erythrophthalmus, Silurus glanis, Squalius cephalus, Thymallus thymallus, Tinca tinca |
| Odonata | Aeshna affinis, Aeshna cyanea, Aeshna grandis, Aeshna isoceles, Aeshna juncea, Aeshna mixta, Anax imperator, Anax parthenope, Brachytron pratense, Calopteryx splendens, Calopteryx virgo, Coenagrion hastulatum, Coenagrion puella, Coenagrion pulchellum, Cordulegaster boltonii, Cordulia aenea, Crocothemis erythraea, Enallagma cyathigerum, Erythromma najas, Erythromma viridulum, Gomphus flavipes, Gomphus vulgatissimus, Ischnura elegans, Ischnura pumilio, Lestes barbarus, Lestes dryas, Lestes sponsa, Lestes virens, Lestes viridis, Leucorrhinia albifrons, Leucorrhinia dubia, Leucorrhinia pectoralis, Leucorrhinia rubicunda, Libellula depressa, Libellula fulva, Libellula quadrimaculata, Ophiogomphus cecilia, Orthetrum cancellatum, Orthetrum coerulescens, Platycnemis pennipes, Pyrrhosoma nymphula, Somatochlora alpestris, Somatochlora flavomaculata, Somatochlora metallica, Sympecma fusca, Sympetrum danae, Sympetrum depressiusculum, Sympetrum flaveolum, Sympetrum pedemontanum, Sympetrum sanguineum, Sympetrum striolatum, Sympetrum vulgatum |
| FW inverts | Adicella reducta, Agapetus fuscipes, Amphinemura standfussi, Apatania fimbriata, Baetis rhodani, Baetis vernus, Brachyptera risi, Brachyptera |

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|---|---|
| (Breitenbach) | seticornis, Centroptilum luteolum, Chaetopteryx villosa, Drusus annulatus, Ephemerella mucronata, Habrophlebia fusca, Habrophlebia lauta, Halesus digitatus, Hydropsyche instabilis, Hydropsyche saxonica, Isoperla goertzi, Isoperla grammatica, Leuctra digitata, Leuctra prima, Lype reducta, Micrasema longulum, Nemoura cambrica, Nemoura cinerea, Nemoura flexuosa, Nemoura marginata, Nemurella pictetii, Odontocerum albicorne, Paraleptophlebia submarginata, Plectrocnemia conspersa, Protonemura auberti, Protonemura intricata, Protonemura meyeri, Sericostoma personatum, Serratella ignita, Silo pallipes, Siphonoperla torrentium, Tinodes rostocki, Wormaldia occipitalis |
| FW inverts (Aubach/Bieber) | Agapetus, Amphinemura, Ancylus fluviatilis, Anomalopterygella chauviniana, Baetis muticus, Baetis niger, Baetis rhodani, Brachyptera risi, Ecclisopteryx dalecarlica, Ecdyonurus venosus, Eiseniella tetraedra, Elmis aenea, Epeorus assimilis, Ephemera danica, Ephemera, Ephemerella mucronata, Gammarus fossarum, Glossosoma conformis, Halesus, Haplotaxis gordioides, Hydraena gracilis, Hydraena, Hydropsyche dinarica, Hydropsyche pellucidula, Hydropsyche siltalai, Isoperla, Lepidostoma basale, Leuctra nigra, Limnius perrisi, Limnius volckmari, Micrasema longulum, Micrasema minimum, Nemoura, Odontocerum albicorne, Orectochilus villosus, Oreodytes sanmarkii, Perlodes, Pisidium, Protonemura, Psychomyia pusilla, Rhithrogena semicolorata, Rhyacophila tristis, Sericostoma, Sialis fuliginosa, Silo nigricornis, Silo pallipes, Silo piceus, Siphonoperla, Stylodrilus heringianus, Tinodes, Torleya major |
| FW phytoplankton | Anabaena spec, Anabaena smithii, Anabaena crassa, Anabaena circinalis, Anabaena flos-aquae, Anabaena spiroides, Ankyra lanceclata, Ankyra spec, Ankyra judayi, Aphanizomenon issatschenkoi, Aphanizomenon gracile, Aphanizomenon flos-aquae, Asterionella formosa, Aulacoseira granulata, Aulacoseira granulata var angustissima f spiralis, Ceratium furcoides, Ceratium hirundinella, Chlamydomonas spec, Chrysochromulina spec, Chrysococcus spp, Closterium spec, Closterium acutum var variabile, Closterium aciculare, Coelastrum microporum, Coelastrum astroideum, Cryptomonas spec, Diatoma tenuis, Dictyosphaerium spp, Dinobryon spec, Dinobryon divergens, Trachelomonas spp, Fragilaria spec, Fragilaria ulna var acus, Fragilaria ulna, Fragilaria ulna angustissima, Fragilaria crotonensis, Gymnodinium spp, Gymnodinium helveticum, Kephyrion spec, Limnothrix spec, Limnothrix redekei, Mallomonas spec, Microcystis wesenbergii, Microcystis spec, Microcystis aeruginosa, Monoraphidium arcuatum, Monoraphidium contortum, Nitzschia spec, Nitzschia fruticosa, Nitzschia fonticola, Nitzschia acicularis, Lagerheimia genevensis, Oocystis spp, Pandorina morum, Pediastrum duplex, Pediastrum boryanum, Peridinium spp, Pteromonas spec, Phacotus lenticularis, Pseudanabaena mucicola, Pseudanabaena spec, Rhodomonas lens, Rhodomonas minuta lacustris, Tetrastrum staurogeniaeforme, Scenedesmus quadricauda, Scenedesmus subspicatus, Scenedesmus opoliensis, Scenedesmus armatus, Synura spec, Synura uvella |
| Marine fish (NS-IBTS) | Agonus cataphractus, Alosa alosa*, Alosa fallax, Amblyraja radiata, Ammodytes marinus, Ammodytes tobianus, Anarhichas lupus, Arnoglossus laterna, Buglossidium luteum, Callionymus lyra, |

| | Callionymus maculatus, Callionymus reticulatus, Clupea harengus, Cyclopterus lumpus, Echiichthys vipera, Enchelyopus cimbrius, Engraulis encrasicolus, Entelurus aequoreus, Eutrigla gurnardus, Gadus morhua, Gaidropsarus vulgaris, Gasterosteus aculeatus aculeatus, Glyptocephalus cynoglossus, Hippoglossoides platessoides, Hyperoplus lanceolatus, Lepidorhombus whiffiagonis, Limanda limanda, Liparis liparis liparis, Liparis montagui, Lumpenus lampretaeformis, Maurolicus muelleri, Melanogrammus aeglefinus, Merlangius merlangus, Microstomus kitt, Molva molva, Mullus surmuletus, Myoxocephalus scorpius, Pholis gunnellus, Phrynorhombus norvegicus, Platichthys flesus, Pleuronectes platessa, Pollachius virens, Pomatoschistus minutus, Raja clavata, Raja montagui, Sardina pilchardus, Scomber scombrus, Scophthalmus maximus, Scophthalmus rhombus, Scyliorhinus canicula, Solea solea, Sprattus sprattus, Squalus acanthias, Syngnathus acus, Syngnathus rostellatus, Taurulus bubalis, Trachurus trachurus, Trisopterus esmarkii, Trisopterus luscus, Trisopterus minutus, Zeugopterus punctatus |
|---|---|
| Marine fish (BTS) | Agonus cataphractus, Ammodytes marinus, Anguilla anguilla, Arnoglossus laterna, Buglossidium luteum, Callionymus lyra, Callionymus maculatus, Callionymus reticulatus, Chelidonichthys lucerna, Clupea harengus, Cyclopterus lumpus, Dicentrarchus labrax, Echiichthys vipera, Enchelyopus cimbrius, Entelurus aequoreus, Eutrigla gurnardus, Gadus morhua, Hyperoplus lanceolatus, Limanda limanda, Liparis liparis liparis, Merlangius merlangus, Microstomus kitt, Mullus surmuletus, Myoxocephalus scorpius, Platichthys flesus, Pleuronectes platessa, Raja clavata, Scomber scombrus, Scophthalmus maximus, Scophthalmus rhombus, Scyliorhinus canicula, Solea solea, Sprattus sprattus, Syngnathus acus, Syngnathus rostellatus, Trachurus trachurus, Trisopterus luscus, Trisopterus minutus |
| M inverts (Dogger Bank) | Aequipecten opercularis, Aphrodita aculeata, Aporrhais pespelecani, Arctica islandica, Ascidiella scabra, Asterias rubens, Astropecten irregularis, Buccinum undatum, Cancer pagurus, Chamelea striatula, Colus gracilis, Corystes cassivelaunus, Donax vittatus, Ebalia cranchii, Ebalia tumefacta, Echinocardium cordatum, Ensis ensis, Ensis siliqua, Euspira catena, Gari fervensis, Hyas coarctatus, Liocarcinus depurator, Liocarcinus holsatus, Liocarcinus marmoreus, Liocarcinus pusillus, Luidia sarsi, Macropodia rostrata, Mactra stultorum, Neptunea antiqua, Ophiothrix fragilis, Ophiura albida, Ophiura ophiura, Pagurus bernhardus, Pagurus cuanensis, Philocheras trispinosus, Processa modica modica, Psammechinus miliaris |
| M inverts (southern North Sea) | Actiniaria (Actinia equina), Aequipecten opercularis, Anapagurus laevis, Aphrodita aculeata, Aporrhais pespelecani, Ascidiacea (Ascidiella scabra), Asterias rubens, Astropecten irregularis, Brissopsis lyrifera, Buccinum undatum, Colus gracilis, Corystes cassivelaunus, Crangon allmanni, Crangon crangon, Echinocardium spp. (Echinocardium cordatum), Euspira spp.( Euspira pulchella), Galathea spp.( Galathea intermedia), Hyas coarctatus, Liocarcinus holsatus, Luidia sarsi, Macropodia spp.( Macropodia rostrata), Neptunea antiqua, Nucula nitidosa, Ophiothrix fragilis, Ophiura albida, Pagurus bernhardus, Pandalidae(Pandalus montagui), Pennatula phosphorea, Philocheras |

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|---|---|
| | bispinosus, Processa spp.( Processa modica + Processa nouveli holthuisi), Psammechinus miliaris, Turritella communis |
| Marine infauna (TMAP) | Alitta succinea, Alitta virens, Ampharete acutifrons, Aphelochaeta marioni, Arenicola marina, Bathyporeia pilosa, Bathyporeia sarsi, Bylgides sarsi, Capitella capitata, Carcinus maenas, Cerastoderma edule, Corophium volutator, Crangon crangon, Crepidula fornicata, Eteone flava, Eteone longa, Gammarus locusta, Harmothoe impar, Hediste diversicolor, Heteromastus filiformis, Kurtiella bidentata, Lagis koreni, Lanice conchilega, Littorina littorea, Macoma balthica, Malacoceros tetracerus, Mya arenaria, Mytilus edulis, Nephtys hombergii, Phaxas pellucidus, Phyllodoce mucosa, Pygospio elegans, Retusa obtusa, Scoloplos armiger, Spio martinensis, Streblospio shrubsolii, Tubificoides benedii |
| Marine phytoplankton | Asterionellopsis glacialis, Ceratium furca, Ceratium fusus, Ceratium horridum, Cylindrotheca closterium, Guinardia delicatula, Odontella aurita, Paralia sulcata, Thalassionema nitzschioides |

*Alosa alosa* is a rare species (narrowly passing our inclusion criterion) and this species may have been misidentified. However, as a rule, we assumed the species identification in the ICES dataset was correct. In any case, the exclusion of this species has little effect on the results.

Supplementary information for:

Cross-realm assessment of climate-change impacts on species' abundance trends – Bowler et al.

**Supplementary Table 3**. Attributes tested for each group. Included are the correlation coefficients of each variable's association with population trends. The correlation coefficient is emboldened and italicized when significant. Correlation coefficients vary between -1 and 1, indicating a negative or positive relationship respectively. All variables were tested in a regression model that included the significant attribute variables as predictors and population trend as the response. In cases of categorical variables, we present the effect size of the largest pairwise contrast.

| Taxa | Sensitivity to climate change | Sensitivity to other environmental drivers | "Adaptive capacity" (attributes that affect how individuals cope with change) | "Resilience" (attributes that affect how quickly population changes) | Other attributes |
|---|---|---|---|---|---|
| General prediction | Temperature preference positively related to population trends i.e., warmer-adapted species have more positive trends<br><br>Temperature range is also predicted to be positively related to trends, i.e., species with | Land use - Species associated with land use types that have increase in extent or decreased in intensity of use should increase<br><br>Pollution – pollution tolerant/preference for higher nutrient loads species should show more positive trends | Organisms with attributes likely to confer adaptive capacity (e.g., broader habitat niche, higher dispersal ability) show more positive population trends and a negative interaction with temperature preference | Organisms with attributes that increase speed of response to environmental drivers (e.g., a short generation time) should show more negative trends, assuming drivers have persistent negative effects | Taxa-specific attributes that might affect population trends in indirect ways |

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| | a broader range have more positive trends | than pollution intolerant species<br><br>Exploitation – species that are exploited should show more negative trends | | (opposite effect might be apparent if impacts driven by extreme events) | |
| Bats | Temperature preference (polygon range maps[1])<br><br>(correlation between temperature preference and population trend = 0.05)<br><br>(correlation between temperature range and population trend = **0.64**) | Habitat breadth (forest dependent or not)[2]<br><br>(correlation between habitat breadth and population trend = 0.11) | | | Body mass[2]<br><br>(correlation between mass and population trend = -0.42) |
| Birds | Temperature preference (polygon range maps[3])<br><br>(preference = **0.24**)<br><br>(range = - 0.10) | Main breeding habitat (urban, wetland, farmland, forest)[4]<br><br>(forest vs farmland = **0.29**) | residual (after body mass) Kipp's distance[5]<br><br>(-0.11)<br><br>Habitat breadth[6]<br><br>(-0.04) | Annual fecundity[6]<br><br>(0.00)<br><br>Age at maturity[7]<br><br>(-0.00) | Diet (invertebrates, omnivore, plant/seeds, predator/scavenger)[8]<br><br>(invertebrates vs predator/scavenger **-0.26**)<br><br>Migration (resident, short, long distance migrant)[4] |

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| | | | | | (long vs resident = **-0.24**)<br>Body mass[8]<br>(-0.01) |
| Butterflies | Temperature preference obtained directly[9]<br>(preference = **0.29**)<br>(range = 0.00) | Grassland use (grassland indicator species or not)[10]<br>(grassland vs not = 0.05) | Habitat breadth (number of habitats used)[11]<br>(-0.03)<br>Dispersal index[12]<br>(-0.06) | Development time[12]<br>(0.08)<br>Potential fecundity[12]<br>(0.02) | Male forewing length[13]<br>(**-0.24**)<br>Diet (mono, oligo, mono)[12]<br>(poly vs mono, **0.20**) |
| Ground beetles (Belgium) | Temperature preference (polygon range maps[14])<br>(preference = **0.34**)<br>(range = -0.16) | Agricultural land use[14]*<br>(tolerant, some tolerance, sensitive)<br>(sensitive vs some tolerance = 0.10) | Habitat breadth (stenotope, eurytope)[14]<br>(-0.20)<br>Dispersal ability (brachypterous, dimorphic, macropterous)*<br>(dimorphic vs brachy = 0.16) | | Body size[15]<br>(0.08) |

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| Ground beetles (Netherlands) | Temperature preference (polygon range maps[14]) (preference = 0.09) (range = -0.1) | Agricultural land use[14]* (tolerant, some tolerance, sensitive) (sensitive vs tolerance = -0.07) | Habitat breadth (stenotope, eurytope)[16] (0.09) Dispersal ability (brachy, macro, dimorph)[14] (dimorph vs macro = -0.05) | | Body size[15] (**0.39**) |
| Spiders | Temperature preference (country checklists[17]) (preference =0.09) (range = -0.05) | Agricultural land use(can use agricultural land or not)* (can use vs not = 0.04) | Habitat structure breadth[18] (0.00) Ballooning ability (yes, no)[19] (0.03) | | Moisture preference breadth [18] (**0.33**) Body size[20] (**0.33**) |
| Springtails | Temperature preference (country checklists[17]) (preference = **0.23**) (range = -0.09) | Forest use % [21] (**0.25**) Deciduous vs coniferous use [21] (**0.25**) | Habitat breadth[21]§ (0.02) | | Body length[22] (**-0.43**) |
| Myriapods | Temperature preference (country checklists[17]) (preference = 0.03) (range = 0.07) | Forest use % [21] (-0.20) | Habitat breadth[21]§ (0.00) Movement speed (fast, slow)* | Life cycle (one year or more)* (-0.16) | Body length[23] (-0.06) |

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| | | | (-0.14) | | |
| Dry grassland plants | Temperature preference (point occurrence records from GBIF and distribution maps[24, 25, 26]) (preference = 0.22) (range =0.09) | Ellenberg N[27] (0.26) | Habitat breadth (number of hemerobic levels)[28] (0.06) Dispersal index[29] (0.16) | Life span (annual, perennial)[30] (-0.24) | Leaf persistence[28] (persistent green versus not, -0.12) |
| Lichen | Temperature preference (point occurrence records from the GBIF) (preference = **0.43**) (range = -0.08) | Wirth indicator values[31] light (*-0.39*) nitrogen (**0.37**) | Habitat substrate breadth[31] (2 vs 1 substrate types = -0.04) | | |
| Freshwater Fish (lake) | Temperature preference (polygon range maps[32]) (preference = -0.04) (range = 0.11) Stream zonation preference (-0.33)[33] | Water quality flexibility[34] (-0.28) | Dispersal ability (shape factor, 3 levels )[35] (0.24) Habitat breadth (lim/rheo specialist or generalist)[35] (-0.23) | Age at maturation[35] (-0.10) Life span (< 8, 8 to 15, > 15) [35] (>15 vs <8 = -0.23) | Body length class (<=20, 20-39, >=39)[35] (>=39 vs <=20 = -0.25) |
| Freshwater Fish | Temperature preference (polygon range maps[32]) | Water quality flexibility[34] (**-0.57**) | Dispersal ability (shape factor, 4 levels)[35] (-0.08) | Age at maturation[35] (0.17) | Body length class (<=20, 20-39, >=39)[35] |

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|---|---|---|---|---|---|
| (river) | (preference = -0.00)<br>(range = -0.23)<br>Stream zonation preference (0.11)[33] | Exploitation*<br>(-0.20) | Habitat breadth (lim/rheo specialist or generalist)[35]<br>(-0.14) | Life span (< 8, 8 to 15, > 15) [35]<br>(>15 vs <8 = **-0.39**) | (>=39 vs <=20 = -0.08) |
| Odonata | Temperature preference (polygon range maps[36])<br>(preference = 0.22)<br>(range = 0.12) | Saprobitic index[35]<br>(organic pollution)<br>(-0.22) | Habitat breadth(specialist, generalist)[36]<br>(0.05) | Larval development time[37]<br>(-0.18)<br>Hind wing length (probably relates to dispersal ability)[36]<br>(**-0.44**) | |
| Freshwater Invertebrates (Breitenbach) | Temperature preference (point occurrence records from the GBIF, STAR and Zobodat databases)<br>(preference =0.06)<br>(range =0.08)<br>Stream zonation preference[35]<br>(0.08) | Saprobitic index (organic pollution)[35]<br>(0.10) | Dispersal[38]$<br>(-0.02)<br>Habitat breadth[38]§<br>(-0.19) | Life cycle duration$[38]<br>(0.12) | Size[38]<br>(**0.35**) |
| Freshwater Invertebrates | Temperature preference (point occurrence | Saprobitic index (organic pollution)[35] | Dispersal[38]$<br>(0.05) | Life cycle duration[38]$ | Size[38]<br>(**0.29**) |

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| (Aubach/Bieber) | records from the GBIF, STAR and Zobodat databases) (preference = -0.12) (range = -0.04) Stream zonation preference[38] (-0.12) | (-0.18) | Habitat breadth[38]§ (-0.22) | (-0.10) | |
| Freshwater phytoplankton | Temperature preference (based on average daily water temperature when species was present, weighted by abundance) (preference = 0.02) | Nitrogen fixation ability* (0.12) | | Maximum growth rate[39] (*-0.31*) | Diameter[39] (0.08) |
| Marine fish (NS-IBTS) | Temperature preference (Point occurrence records from the GBIF and OBIS) (preference = *0.26*) (range = -0.13) | Exploitation (major commercial/commercial vs minor commercial/not fished)[40] (major versus not fished = *-0.38*) | Range size (-0.03) | Age at sexual maturity[41] (correlated with length) | Maximum length[41] (-0.17) |

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|---|---|---|---|---|---|
| Marine fish (BTS) | Temperature preference (Point occurrence records from the GBIF and OBIS) (preference = 0.06) (range = -0.08) | Exploitation (major commercial/commercial vs minor commercial/not fished)[40] (major versus not fished = **-0.40**) | Range size (-0.16) | Age at sexual maturity[41] (correlated strongly with length) | Maximum length[41] (-0.11) |
| Marine benthic invertebrates (southern North Sea) | Temperature preference (Point occurrence records from the GBIF and OBIS) (preference = -0.02) (range = 0.01) | | Range size (-0.09) Adult mobility[42, 43]$ (0.06) | Age at maturity[42, 43]$ (-0.10) Longevity[42, 43]$ (-0.21) | Body size[42, 43]$ (0.12) |
| Marine benthic invertebrates (Dogger Bank) | Temperature preference (Point occurrence records from the GBIF and OBIS) (preference = 0.12) (range **= 0.38**) | | Range size (0.01) Adult mobility[42, 43]$ (-0.02) | Age at maturity[42, 43]$ (0.23) Longevity[42, 43]$ (0.04) | Body size[42, 43]$ (0.11) |
| Marine infauna (TMAP) | Temperature preference (Point occurrence | | Range size (**-0.53**) | Age at maturity[43] (-0.14) | Body size[43] (-0.01) |

| | | | | | |
|---|---|---|---|---|---|
| | records from the GBIF and OBIS)<br><br>(preference = 0.12)<br><br>(range = 0.03) | | Adult mobility[43]$<br><br>(-0.12) | Longevity[43]<br><br>(-0.28) | |
| Marine phytoplankton | Temperature preference (point occurrence records from the GBIF and OBIS)<br><br>(preference = -0.37)<br><br>(range =-0.44) | | Range size<br><br>(-0.29) | | Size*<br><br>(-0.03) |

\* indicates that the data were based on expert assessment; § indicates that habitat breadth was based on coefficient of variation (\*-1) of species affinities to different habitat categories; $ data were fuzzy coded and condensed into a single variable by taking a weighted average

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Supplementary information for:

Cross-realm assessment of climate-change impacts on species' abundance trends

– Bowler et al.

**Supplementary Table 4**. Meta-analysis of dataset-level characteristics potentially affecting the effect size of temperature preference on population trends. Significant variables were centered and included in the meta-analysis to be able to predict average effects of temperature preference in each realm at average dataset-level characteristics.

| Standardized variable | Effect (SE) | Statistic (LRT) | P-value |
|---|---|---|---|
| (ln) No. species | 0.122 (0.040) | 7.501 | 0.006 |
| Start year | -0.084 (0.034) | 4.567 | 0.033 |
| Time span | 0.047 (0.037) | 1.511 | 0.219 |
| (ln) Sampling sites | 0.1004(0.030) | 10.271 | 0.001 |
| Temperature trend | 0.049 (0.035) | 1.796 | 0.180 |

**Supplementary tables**

**Supplementary Table 5** Temperature trends (of 3-year smoothed mean), as well as comments on other drivers hypothesized to be important in each dataset.* P<0.05, **P<0.01, ***P<0.001

| Taxa | Temperature change (°C y⁻¹) (1980 –2010) | Temperature change (°C y⁻¹) (over study period) | Other drivers in the surrounding landscape. |
|---|---|---|---|
| Bats | 0.0463* (SE, 0.0187) | 0.0060 (SE, 0.0245) | Recovery following decline due to intensive agriculture, land use, persecution[1]. |
| Birds | 0.0414** (0.0147) | 0.064** (0.0212) | Wetland protection/restoration. Agricultural intensification[2]. |
| Butterflies | 0.0331 (0.0246) | 0.0368 (0.0214) | Probable loss of grassland[3]. |
| Ground beetles (Belgium) | 0.0306 (0.0580) | 0.0548** (0.0165) | None. |
| Ground beetles (Netherlands) | 0.0520* (0.0222) | 0.05109 (0.0488) | Some local management activities[4]: since 1980 recovery from previous acidification and restoration of original hydrology. |
| Spiders | 0.0306 (0.0580) | 0.0015 (0.0314) | None. |
| Springtails | 0.0374 (0.0209) | 0.0912 (0.0482) | Probable forest maturation. |
| Myriapods | 0.04101 (0.0250) | 0.0198 (0.0354) | Probable forest maturation. |
| Dry grass plants | 0.04264 (0.0233) | 0.0539 (0.0300) | Not managed, rare sheep grazing[5]. |
| Lichen | 0.0518* (0.0222) | 0.0276 (0.0352) | Pollution - increased N, decreased $SO_2$[6]. |
| FW fish (lake)[a] | 0.0531** | 0.0072 (0.030) | Nutrient levels peaked around 1980 and have declined since |

| | | | – currently oligotrophic[7]. |
|---|---|---|---|
| | (0.0128) | | |
| FW fish (riverine) | 0.0442 (0.0239) | 0.0136 (0.0380) | River restoration measures (hydromorphology, water quality)[8]. |
| Odonata | 0.0331 (0.0246) | -0.0014 (0.0321) | None relevant known. |
| FW inverts (Breitenbach) | 0.0468* (0.0212) | 0.0935 (0.0895) | None. |
| FW inverts (Hesse) | 0.0382 (0.0619) | -0.0358 (0.0252) | Limited water quality data available. Slight decrease in nutrients since 2005. |
| FW plankton[b] | 0.0519** 0.0140 | 0.0147 (0.0151) | Decreases in external nutrient load since the early 1990s[9]. |
| Marine fish (NS-IBTS)[c] | 0.0519* (0.0231) | 0.0312 (0.0429) | Fishing (predominantly trawling). |
| Marine fish (BTS)[c] | 0.0317 (0.033) | 0.0312 (0.046) | Fishing (predominantly trawling). |
| Marine inverts (Dogger Bank)[c] | 0.0351 (0.0215) | -0.0272 (0.0419) | Fishing (predominantly trawling). |
| Marine inverts (southern North Sea)[c] | 0.0519* (0.0231) | 0.0467 (0.0586) | Fishing (predominantly trawling). |
| Marine infauna (TMAP)[c] | 0.0741** (0.0174) | 0.0859 (0.0184)*** | Nutrient and heavy metal pollution, fishing impacts. |
| Marine phytoplankton[d] | 0.0510** (0.0180) | 0.0510** (0.0180) | Increased salinity and decreased nutrient input since 1980s[10]. |

[a]Water temperature available from BOWIS – Bodensee-Wasserinformationssystem der Internationalen Gewässerschutzkommission für den Bodensee (IGKB); [b]Water temperature from data owner; [c]Bottom water temperature from ICES; [d]Surface water temperature from data owner.

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