Widespread decline of ground beetles in Germany

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Author contributions

SC, DB, HB, FJ, RK, MW, and AB conceptualised the idea and developed the method; SC and DB did the analysis; everyone contributed to the analysis; SC wrote the paper; everyone contributed to the writing.

Abstract

Many insect species are facing existential crises, primarily due to diverse human-induced activities. Most insect assessments, however, are based on short-term data or some iconic species. Here, in close collaboration with taxonomic experts from natural history societies, we compiled the best available occurrence data for ground beetles in Germany, estimated the changes in species occupancy over the last 36 years, and related these changes to the traits/characteristics of these species. We obtained trends for 383 species and found that 52% of species significantly declined, and 22% significantly increased in site occupancy. The remainder of the species (26%) all showed a mean negative trend, albeit nonsignificant. Interestingly, non-threatened species declined at a similar rate to the threatened species, with 64% of the Near Threatened species experiencing significant declines (highest among all red list categories). Across all traits, we found that large (compared to medium) and omnivore (compared to predator) species declined less. Considering that ground beetles are key predators in many ecosystems and in agricultural systems that play an important role in pest control and in the food chain, their decline should raise concerns. Thus, we urgently plead for more harmonised and systematic monitoring of this insect group.

Keywords

Citizen science, insect decline, insect conservation, insect monitoring, long-term change, occupancy detection model, trend analysis

Introduction

We are currently in the midst of a biodiversity crisis (Dirzo et al., 2014; Leclère et al., 2020). Human activities, particularly habitat destruction and alteration, have caused a precipitous decline in many species across various taxa (Butchart et al., 2010; Bellard et al., 2012; Haddad et al., 2015; Eichenberg et al., 2021; Jandt et al., 2022). The Living Planet Report revealed a shocking 69% drop in the population abundance of vertebrates over the last 49 years (WWF, 2022). However, such global reports often overlook insects (Dove et al., 2023; Ledger et al., 2023). Despite the fact that insects are “the little things that run the world” (Wilson, 1987), there are significantly fewer conservation assessments on insects than on vertebrates (Chowdhury et al., 2023a; Samways et al., 2020). This disparity is also evident in species extinction risk assessments: only 8% of the assessed species in the IUCN Red List are insects (IUCN, 2024), even though insects comprise over 80% of animal species on Earth (Stork, 2018). The massive underrepresentation of insects in the global extinction risk assessments is primarily due to insufficient data on the occurrence of most species (Didham et al., 2020; Chowdhury et al., 2023b). For example, about 65% of the species occurrence data in the Global Biodiversity Information Facility (GBIF) are for birds, while less than 9% of the records are for insects (data accessed on June 9, 2024). Although insect occurrence data have surged over the last one and half decades mostly due to citizen involvement (Heberling et al., 2021), these new data are usually spatially and taxonomically biased and cannot be compared to previous decades of specimen-based collections.

The loss of insect biodiversity has received much less attention than that of vertebrates, yet insect decline is a global issue (Dirzo et al., 2014; Eisenhauer et al., 2019). Dunn (2005) estimated that if the extinction rate of insects is similar to that of birds, nearly 44,000 insect species have already gone extinct, yet only 70 insect extinctions have been documented. Recent studies have revealed that many insect species are declining dramatically worldwide (Didham et al., 1996; van Klink et al., 2020, 2023; Wagner, 2020; Wagner et al., 2021). For example, over 75% of insect biomass has declined in some protected areas in Western Germany (Hallmann et al., 2017), over 80% of butterfly species have declined in the Netherlands over the last century (van Strien et al., 2019), 29% of odonate species have declined from 1980-2016 in Germany (Bowler et al., 2021). Although many threats are interactively impacting species conservation status and trends, anthropogenic climate change and habitat change by intensive agriculture are the main drivers of global insect declines (Dieker et al., 2011; Halsch et al., 2021; Raven & Wagner, 2021; Outhwaite et al., 2022).

From all these underrepresented invertebrates, carabids are one of the most frequently sampled taxa and are used in ecological studies about drivers and planning assessments (Rainio & Niemelä, 2003; Avgin & Luff, 2010; Kotze et al., 2011). Carabids are often used as a bioindicator group. They play important ecosystem functions, on the one hand as predator and biological control agents (Sharavari et al., 2017), and on the other hand as prey for birds and small mammals. There is a good knowledge of ecological requirements/niches of most of the prominent species (Rainio & Niemelä, 2003; Avgin & Luff, 2010; Kotze et al., 2011). Comparative studies have shown that large poorly dispersing specialist species commonly decrease, while generalist good dispersers tend to increase (Kotze & O’Hara, 2003). In Germany, the latest national Red List reported 35% of carabid species as either threatened or already extinct (Schmidt et al., 2016). Some local studies assessed the trends of carabids in Germany: the species richness and phylogenetic diversity, but not biomass, has declined in a forest over 24 years, (Homburg et al., 2019). By assessing traits of the current Red List species of Germany, Nolte et al (2019) showed that carabid species associated with mountainous, coastal and open habitats are at a higher risk of extinction compared to most forest associated species. Here, by compiling carabid data using various approaches, we analyse the long-term trends of carabid beetles in Germany for the past 36 years and assess if the changes in occupied sites are related to species traits and national threatened status.

To meet the Kunming-Montreal global biodiversity framework targets (CBD, 2022), acting on insect conservation is now a priority. Identifying the state of species, the pattern and reasons of decline is crucial. However, estimating changes in species occupancy is aided by long-term systematic data, which are unavailable from most of the world. Instead, there is a large amount of heterogeneous data, collected either opportunistically or with unknown methods. If such data are analysed with naive methods, there is the danger of producing biased estimates or having a low power to detect trends (Isaac et al., 2014). While different types of statistical models exist to analyse population trends using heterogeneous data, the occupancy detection model is the most reliable (Isaac et al., 2014; Outhwaite et al., 2019; Bowler et al., 2022).

Based on almost 1 million records of occurrences of 554 species collected by German volunteers and carabid experts, we assessed the changes in occupancy of carabid beetles in Germany over the last 36 years (1988-2023). Using single-species multi-season occupancy models (Doser et al., 2022), we investigated the changes in occupancy patterns. We further collated species attributes to compare whether changes in species occupancy were associated with conservation status or morphological and ecological traits. This is the first-ever national-scale statistical assessment of carabid beetle trends in Germany, highlighting the potential impact on policy and helping Germany meet the global biodiversity framework obligations.

Methods

Occurrence data

We collated species occurrence data in direct collaboration with German carabid experts. We compiled the data in two steps. First, we obtained species occurrence data from the ColeoWeb (https://www.coleoweb.de/) database (Bleich et al., 2024). This is the most comprehensive database for German beetles, which includes data on carabid beetles that originate mostly from systematic pitfall trapping, supplemented by data from hand collecting and opportunistic observations. This initial data collation included 586,292 occurrence records for 554 species. Because this dataset did not contain the most recent data that carabidologists have collected, we attended the annual meeting of the German Carabid Society (GAC, http://www.angewandte-carabidologie.de/) in February 2024 in Göttingen. We requested the members to share their unsubmitted observations within three months (by May 2024) with the ColeoWeb database. This way, we updated the dataset to 953,230 occurrence records for 554 species.

Data cleaning

Once we obtained the compiled data, we cleaned the dataset following several approaches. First, we harmonised species names and removed records without location information (longitude and latitude), date (day, month and year), duplicate records, and imprecise coordinates (records in the ocean or outside German borders).

We only included occurrence records for the last 36 years (from 1988 to 2023). We chose 1988 as the first year because the occurrence records were substantially fewer in the earlier years. The yearly species occurrence records were low for many species, so we grouped years into 2-year bins, resulting in 18 bins for the 36-year study period (1988-2023). After a peak in observations around the year 2000, the number of observations has fallen again in recent years (Figure 1b). We grouped occurrence records into survey quadrants with an edge length of 10 minutes longitude and 6 minutes latitude, which is approximately 11 x 11 km (German Ordnance Map, Meßtischblatt, MTB). The number of survey quadrants has increased over time (Figure 1c). We discussed this issue with the experts, who suggested that this reflects a change in observer behaviour, with many observers now exploring new areas rather than visiting the same sites. To estimate the changes in 2-year bins, we only included survey quadrants visited at least twice in the last 36 years (Outhwaite et al., 2018; Bowler et al., 2022). Our final cleaned dataset included 602,108 occurrence records for 554 species with a median of 346 occurrence records per species (Figure 1a). The number of occurrence records was low for many species: 71 with < 10 and 173 with < 100; however, the occurrence records were well-distributed across the entire study period. For example, we had data from 7 year-bins from at least 50% of the survey quadrants.

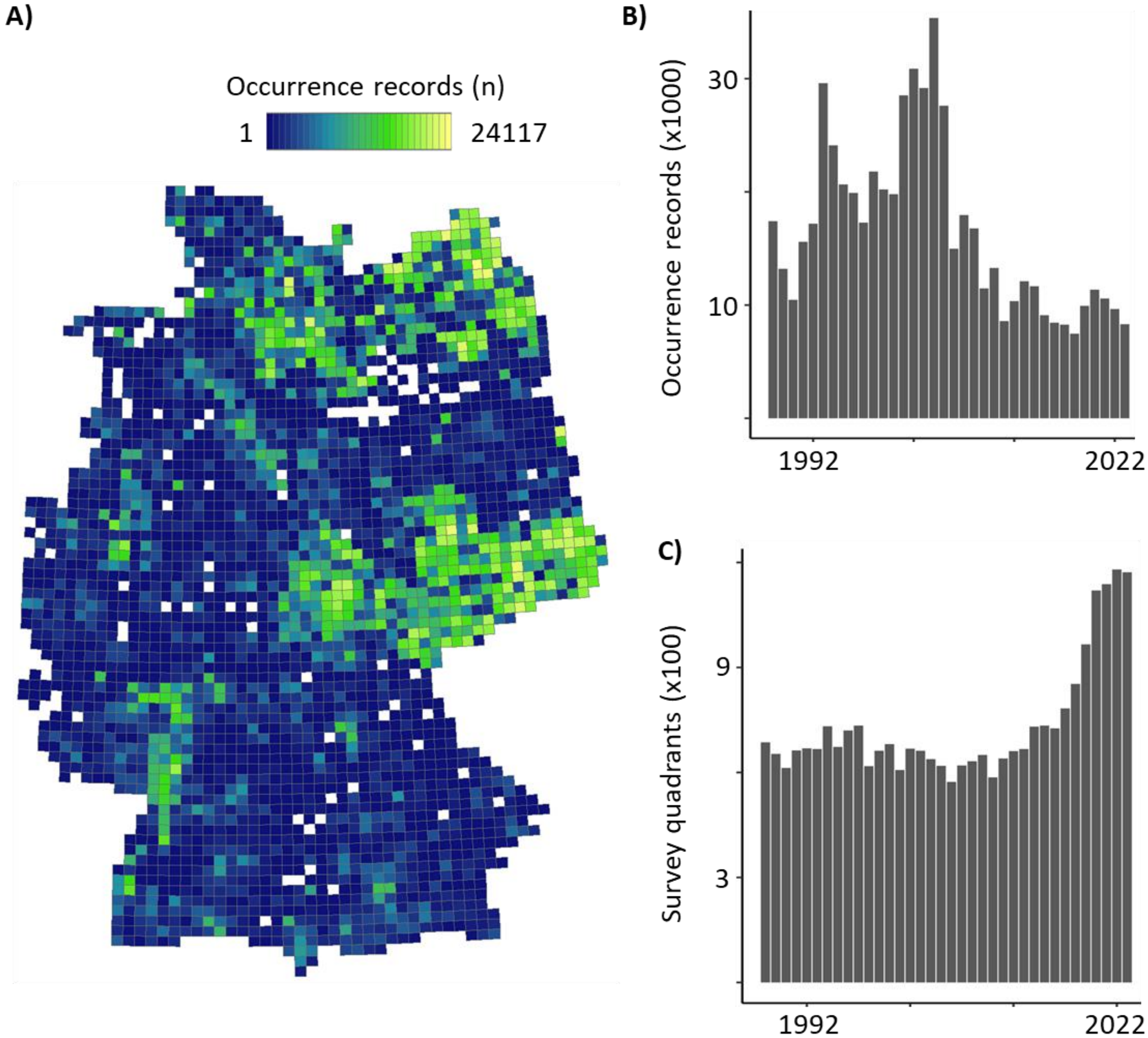

Figure 1. The patterns of distribution records of carabid beetles in Germany (1988-2023). A) is the spatial distribution of records for all species and years (colours reflect the number of records in each MTB grid cell, where 'white' indicates no data from that grid); B) is the number of species occurrence records per year; and C) is the number of survey quadrants per year with at least one species record.

Trend estimation

To estimate the changes in the occupancy of carabid beetles in Germany, we fitted single-species multi-season occupancy detection models. Occupancy-detection models are one of the best methods to estimate trends in heterogeneous occurrence data sources and are designed to accommodate variability in detection probabilities (Isaac et al., 2014).

As the unit of the detection model, we aggregated observations into those likely to be collected on the same survey visit. A visit was defined by species observations collected on the same date in the same survey quadrant (van Strien et al., 2010; Bowler et al., 2022). We inferred the absences of species (non-detections) based on observations of other species during a given visit (Outhwaite et al., 2020), similar to the commonly used target-background method used in species distribution models (Ranc et al., 2017; Barber et al., 2021). Since some sites were sampled much more than others, we subsampled at most 10 visits per year at any specific site (i.e., survey quadrant). We built models for species with at least 50 occurrence records (76% of species in the dataset).

We modelled occurrence probability as a function of site and year variation. Here, the year variation was modelled by including the 2-year bins (due to data sparsity in some years) as a fixed continuous effect and site variation as a random effect to account for mean spatial variation in occupancy. We modelled the detection probability for each visit to a given quadrant in a 2-year bin. Survey effort was included in the detection model using list length as a proxy variable: (Outhwaite et al., 2019). Specifically, list length was the number of species reported on a visit (categorical variables with three levels: a single list (1 species, 53% visits), a short list (2–3 species, 21% visits) or a longer list (4 or more species, 26% visits, set as the reference level). We separately fit the model for each species. The observed detection data for a given species on each visit were assumed to be derived from a Bernoulli distribution conditional on the presence of the species in that survey quadrant and a 2-year bin.

We fit the model using the spOccupancy package (Doser et al., 2022) in R (R Core Team 2024; Version 4.2.0) by Bayesian inference using Markov chain Monte Carlo simulation. We used vague priors and 3 chains with 150000 iterations, discarding the first three-quarters as burn-in. We assessed model convergence using Rhat statistics and trace plots. We carried out posterior predictive checks by calculating a Bayesian p-value with a Freeman-Turkey fit statistic. In the end, we obtained trends for 383 species (69% of 554 initial species). The model convergence/performance is good when the Rhat value is < 1.1, and the Bayesian p-value ranges between 0.1 and 0.9 (Doser et al., 2022). Based on this, the model performance was sufficient in our case, with a mean Rhat value of 1.012 (median 1.007) and a mean Bayesian p-value of 0.45 (median 0.45). Four German carabid experts also thoroughly examined the predicted trends for each species to check for plausibility.

To test whether the survey bias had any impact on our result, we ran a sensitivity analysis. We removed the two data-dense states (Mecklenburg-Vorpommern and Saxony) from the cleaned dataset and ran the single-species multi-season occupancy model following the method described above. We discussed the results in the results section and added the figure in the supplementary section (Supplementary Figure S1).

Species attributes

To explain variation in the trends of different species, we collated two types of trait data. First, we obtained the threat status of each carabid species from the German Red List (Schmidt et al., 2016). Second, we combined species traits from the ColeoWeb database and Nolte et al. (2017). Specifically, we collated species information on mean body size (numerical), wing types (categorical; short-winged, dimorphic, and long-winged), trophic level (categorical; herbivore, mycetophag, omnivore, and predator), and habitat preference (categorical: coastal, eurytopic, forest, mountain, open, riparian, special habitat, and wetland). To test if the trend was significantly associated with any of the species attributes, we fitted a linear model considering species trend with all attributes, calculated using the occupancy-detection model, as the response variable and species attributes as the explanatory variables.

Results

Of the 383 species, for which we obtained occupancy trends for (i.e., bi-annual changes in the number of occupied survey quadrants), the trend was negative for 78% of species (298 species) and positive for 22% of species (85 species). Based on whether the 95% CI of trend overlapped zero, we identified that 52% of species (200 species) significantly declined, while 22% (85 species) significantly increased. The trend was insignificant (or stable) for the other 26% of species (98 species) (Figure 2). We obtained a very similar result ($|r| = 0.94$) in the sensitivity analysis, meaning that the survey bias did not have any impact on our findings (Supplementary Figure S1).

For species that had significantly declined, the trend was highest for *Trechus pulchellus* (trend estimate: -0.31; 95% CI = -0.46, -0.18). For species that had significantly increased, the trend was highest for *Elaphropus diabrachys* (trend estimate: 0.25; 95% CI = 0.19, 0.33). The mean and median trend for the significantly decreasing species was -0.1 and -0.09 respectively; while the median trend for the significantly increasing species was 0.04. For 98 species, we obtained insignificant trends; all showed slightly negative trends and were very close to zero (except for one species, *Stenolophus teutonus*; trend: -0.13) (Figure 2).

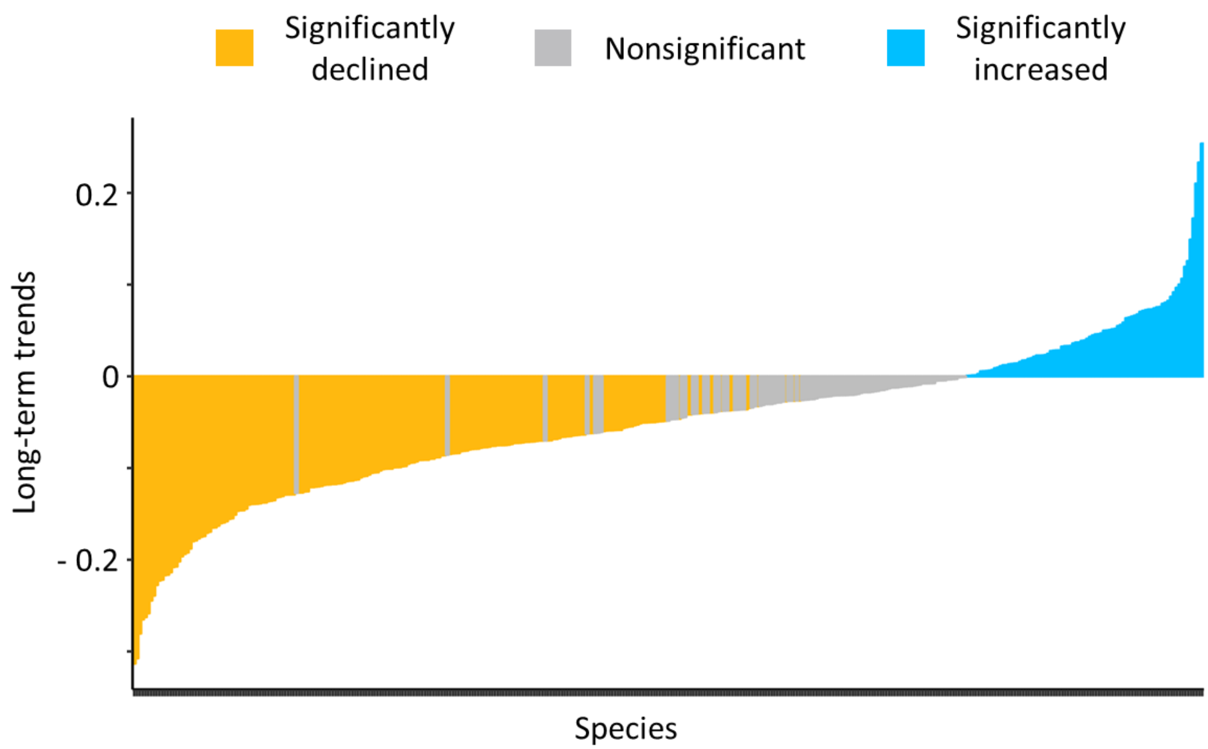

Figure 2. The bi-annual changes in the number of occupied survey quadrants of carabid beetle occupancy in Germany over the last 36 years. Here, each bar represents one species.

The 383 species for which we could calculate trends contained 278 non-threatened species, 104 threatened species, and only one species that was listed as Data Deficient in the German Red List (*Philorhizus quadrisignatus*). The overall changes in the proportion of occupied sites were somewhat similar among the threatened and non-threatened species. Of the 278 non-threatened species, 53% (148 species) significantly declined, 23% (63 species) significantly increased, and the trend was non-significant for 24% (67 species). In contrast, among the threatened species, 50% (52 species) significantly declined, 21% (22 species) significantly increased, and the trend was non-significant for 29% (30 species) (Figure 3). Among the species that had significantly declined over the last 36 years, the percentages were the highest for the Near Threatened species (64%; 32 of 50 species) and lowest for the Rare species (40%; 2 of 5 species). However, the association between the threatened and non-threatened species was non-significant (Estimate: -0.01, SE: 0.08, Z = -0.21, p = 0.83; generalised linear model).

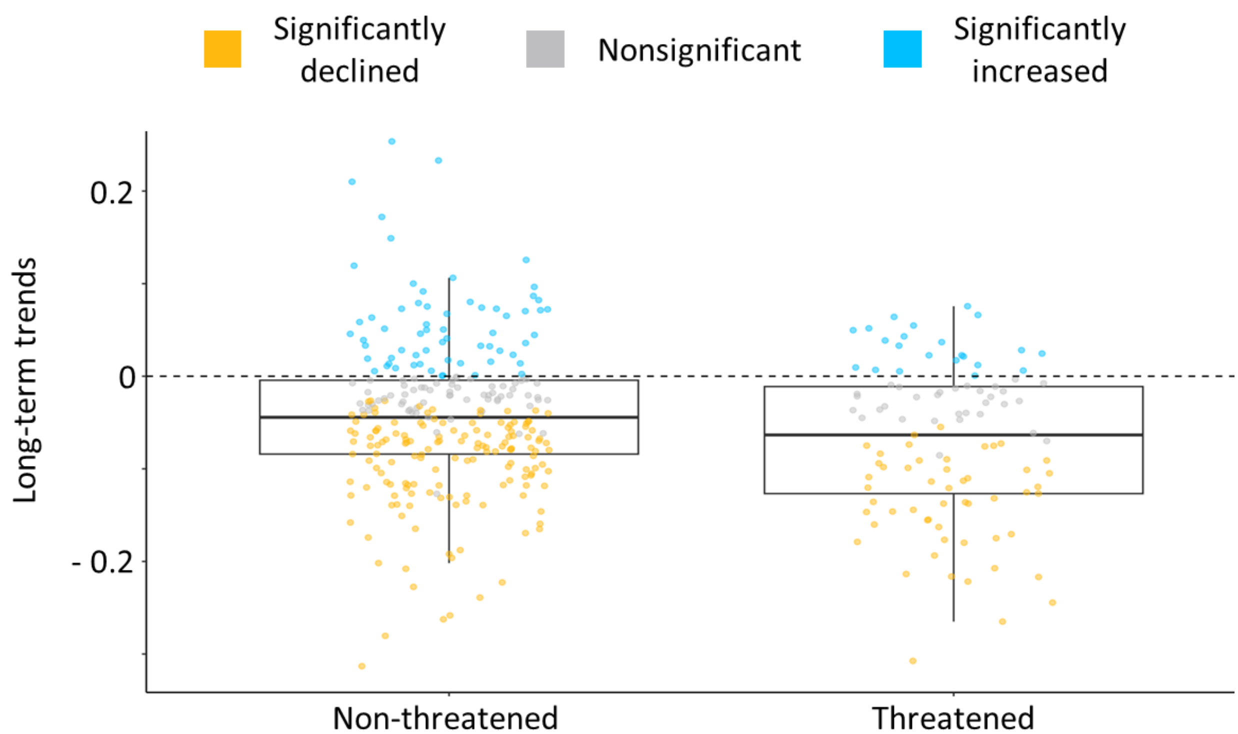

Figure 3. Trends of German carabid beetles based on their national threat status. Each point shows a species, colours by its trend classification. The boxplot shows the median, interquartile range and range of the species trends. There was no significant difference between the trends of threatened and non-threatened species, albeit the trends were more negative for the former.

The median bi-annual changes in the proportion of occupied sites were somewhat similar across wing types (Figure 4A), whereas, for trophic level status, the median trend was slightly less declining among omnivorous species compared with herbivores (median trend: -0.02 vs -0.05) (Figure 4B). Beetle species with larger body sizes were more often associated with positive trends, whereas smaller species had slightly worse negative trends (Figure 4C). In contrast, regarding habitat preference, the species associated with coastal habitats showed the most negative trends (median trend -0.1), and forest-dwelling species were the least declining (median trend -0.03) (Figure 4D).

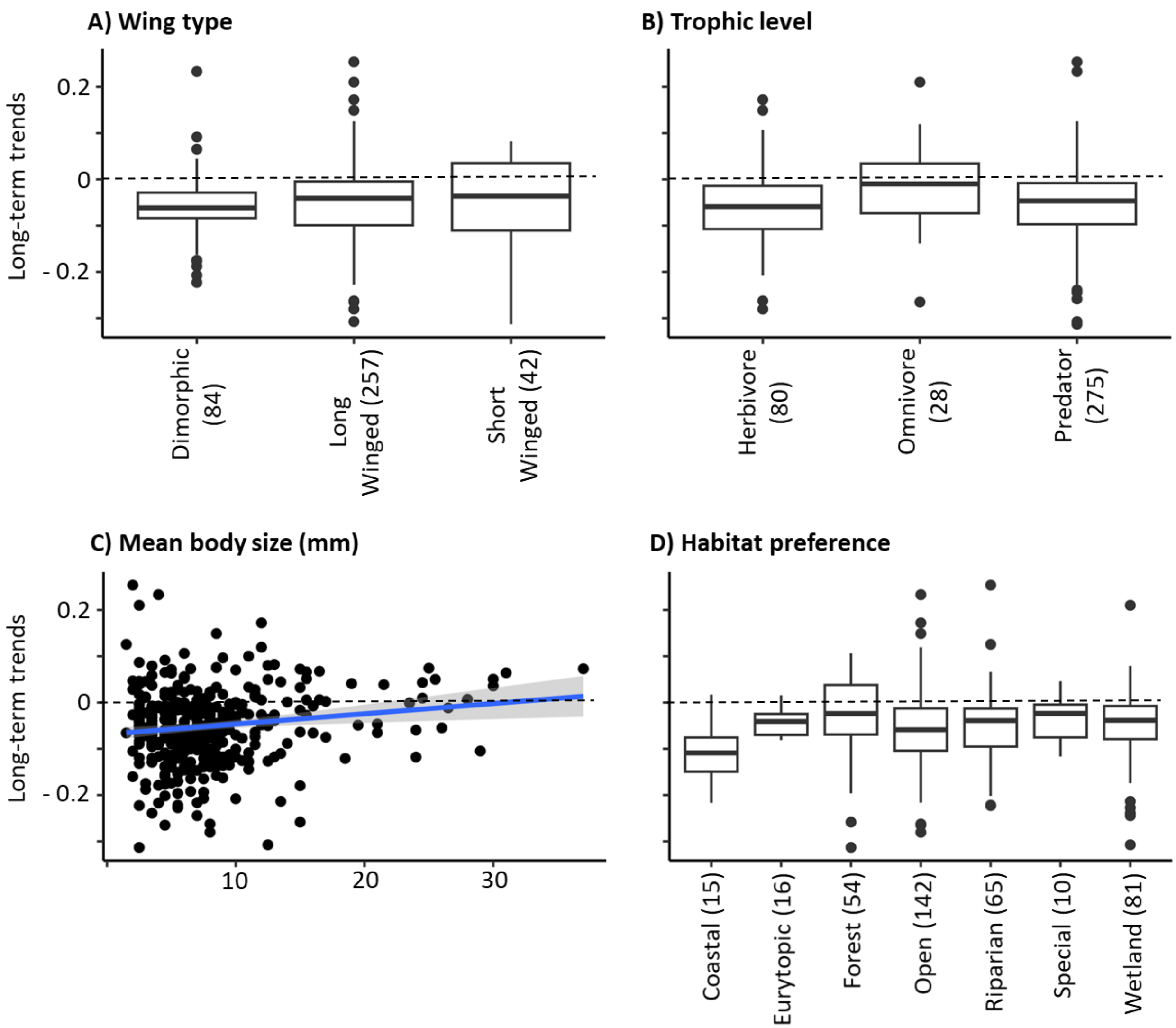

Figure 4. Trends of German carabid beetles based on different morphological traits. A) shows the boxplots of the trends split by wing type; B) split by trophic level; C: by body size (each point shows a species) and D) split by habitat. Here, the horizontal dotted line in each plot indicates no changes.

While the short-winged species had a worse negative trend, the long-winged species had an increasing trend compared to the dimorphic species, but both were non-significant (Figure 5). In contrast to predatory species, both herbivore and omnivore species were increasing, but the association was only significant for the omnivore species (Estimate = 0.04, SE = 0.02, Z = 2.4, p = 0.02) (Figure 5). Among different habitat preferences, coastal species experienced significantly more negative trends (Estimate = -0.06, SE = 0.02, Z = -2.68, p = 0.008), while species with other habitat preferences experienced more positive but non-significantly different trends compared to the open-habitat species (Figure 5). Compared to medium-sized species, both small and large-bodied species had more positive trends, but the difference was only significant for the large species (Estimate = 0.04, SE = 0.01, Z = 3.75, p = 0.0002) (Figure 5).

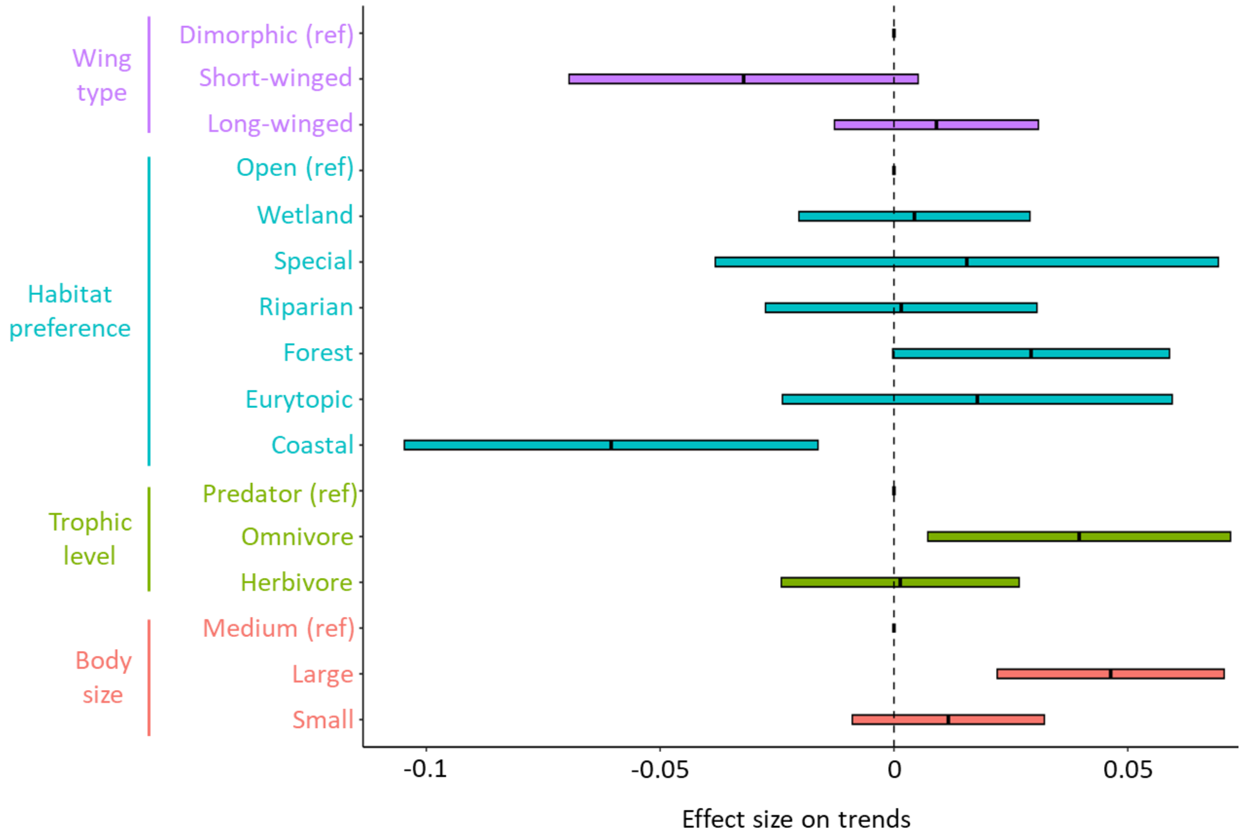

Figure 5. Effect of species attributes on their long-term trend, where the reference groups were shown as points. We fitted a generalised linear model to calculate the effect size. Here, the effect size was assessed by comparison to the trends of reference groups (marked as *ref* in the y-axis, with dimorphic for wing types, predator for trophic level, medium for mean body size, and open habitats for habitat preference), selected by discussing with the carabid experts. For mean body size, we converted the continuous values to three categories: small (1.9-4.5 mm), medium (4.5-10.5 mm), and large (10.5-37 mm).

Discussion

Using the last 36 years (1988-2023) occurrence data of German carabid beetles, we show that nearly 80% of the species have declined in occupancy, and the trend was significant for over half of them (52%). In contrast, only one-fourth of species have increased significantly. Our results of the declining trends are similar to the ones observed in several other insect taxa: 37% of butterflies, dragonflies, and orthopterans have declined in occupancy in Bavaria (Engelhardt et al., 2022), the insect biomass has declined by 10-60 times in Puerto Rico's Luquillo rainforest (Lister & Garcia, 2018), and 80% of the flies have declined in abundance in northeast Greenland (Loboda et al., 2017). Interestingly, our observed changes in species occupancy are quite similar across national threat status classes. While the mean trend of threatened species was slightly lower than the non-threatened species, the association was non-significant. Among the non-threatened group, 64% of Near Threatened species have declined by a mean amount of 8% of their occupied sites.

Species traits are widely considered an important factor in determining species' extinction risk, and changes in species occupancy are associated with species attributes (e.g., Nolte et al., 2019). For example, analysing carabid beetles from Belgium, the Netherlands, and Denmark, Kotze and O'Hara (2003) showed that larger, habitat specialist, short-winged and long-winged species declined more significantly than others. Dimorphic species are usually less prone to extinction because of their ability to disperse (Turin & den Boer, 1988; Kotze & O'hara, 2003). We found that the median trends among different wing types were similar; the trend was slightly better among omnivore species, smaller species were more vulnerable, whereas, among the habitat types, coastal species were the most vulnerable, whereas forest species were least vulnerable. This is in contrast to some of the previous studies where the authors documented coastal and larger species were more vulnerable (e.g., Kotze & O'hara, 2003, but see Nolte et al., 2019). Some authors documented that changes in habitat features, such as climate, land use, and elevation, could have a significant impact on species trends (Desender et al., 2010; Purtauf et al., 2005; Chamberlain et al., 2020; Liu et al., 2021; Skarbek et al., 2021). Future studies could analyse the changes in spatial and temporal occupancy by considering climate, land cover and other features as well as their changes and how species attributes modify their responses to these variables. For example, the species living in forests are generally much larger than those living in dry grasslands. If forests are not threatened at all, as this is the case in Central Europe, a positive trend in large-bodied species is expected.

We followed a crowdsourcing approach to access more data, which increased the data by nearly 40%. We also discussed our results with many carabid experts (some of whom are co-authors) to understand if the bi-annual changes in occupancy matched their expectations and revised the analysis accordingly (e.g., we removed very rare species from the analysis). Despite the various challenges with the data, the trend estimates were broadly in line with the expectations of the experts. Our approach highlights the value of data mobilisation, integration and community involvement for assessing species trends at large scales. However, it should be noted that to be conservative, we only considered expert-verified data, and we did not consider data from GBIF (see Heberling et al., 2021) or social media data (see Chowdhury et al., 2023c, 2024) that may not have been expert validated but might further improve our assessment. Additionally, the number of survey quadrants increased with time, reflecting the change in observer behaviour, with many observers now exploring new areas rather than visiting the same sites. However, occupancy detection models are well-equipped to handle such bias (Isaac et al., 2014; Outhwaite et al., 2018). Our analysis is also limited by the lack of metadata to explain how individual data were collected so we could not fully model the likely sampling variability. We used the list length as a proxy for sampling effort, but this is an imperfect proxy since list length also depends on local species richness (Outhwaite et al. 2018, Szabo et al. 2010). Nonetheless, as we noted above, our trend estimates passed our expert assessment.

Insect decline is a widespread issue. Our study is another example that proves this point. Following expert-driven data compilation and analysis, we show that most ground beetles in Germany have severely declined over the last 36 years. Alarmingly, the number of non-threatened species is declining at a rate similar to that of threatened species.

Data and code availability statement

The trend estimates, trait information and threatened status, are available in the online supplementary material.

All the R scripts are available in the public GitHub repository (https://anonymous.4open.science/r/occ_model_de-15DF/).

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Supplementary Figures

Figure S1

The association between trends with all data and the trends from the sensitivity analysis. The trends from sensitivity analysis were obtained by removing two data-dense states (Mecklenburg-Vorpommern and Saxony) from the cleaned dataset.