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Extensive climate-induced range shifts in butterflies across the globe

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Global changes are leading to widespread species redistribution. Comprehensive assessments of range shift dynamics and their drivers are difficult, partly due to the variation in range shift detection over space and taxa. Here we compile documented range shift records for 1,758 butterfly species from 105 countries and territories, representing ~10% of the known diversity of these insects. Most species (80%) experienced range expansions, and most range shifts (79%) were associated with climate change and extreme weather events. A substantial proportion of species in our dataset contracted their ranges (27%) or shifted along elevational gradients (22%). We report widespread horizontal range expansions and contractions across tropical countries, with less evidence for elevational range shifts. We show that a clearer picture of range shift dynamics emerged only through the combination of different types of data, with expert assessments and non-English studies alleviating potential biases. Our findings of climate-driven range shifts call for concerted efforts to improve inclusive data monitoring and conservation efforts, especially for tropical countries, where human-induced land-use changes exert additional critical pressure.

Anthropogenic pressures, such as land-use and climate changes, are reshaping species distributions worldwide[1–6]. These drivers force species to track favourable environmental conditions by shifting their ranges[1,2,7–10], thereby triggering cascading consequences across ecosystems[2,3,11], resulting in community reshuffling, disrupted coevolved interactions and undermining conservation efforts[2,11,12]. Ranges may shift in multiple directions along latitude, longitude or elevation, leading to both horizontal range expansion and contraction dynamics, as new habitat is gained or lost[13–16], respectively. The colonization or extirpation rates of range-shifting species depend strongly on the interaction between species traits and environmental conditions[3,17,18]. When dispersal capacities are insufficient relative to the pace of environmental change, species may persist in increasingly suboptimal environments, generating a lag between species' realized distributions and their shifting climatic suitability (that is, climatic debt). Accordingly, some species can track their available habitats, while others accumulate climatic debts[8,19,20].

Despite the recent increase in the number of range shift reports, our knowledge remains taxonomically and geographically biased[9,21,22]. Nearly half of the published literature on species redistribution comes from Europe[22], with limited insights from tropical regions, where most biodiversity is concentrated[21,23]. A recent global analysis of 12,415 species identified that flowering plants represented nearly 40% of the reported range shifts, while among animals, birds and fish were the most assessed taxonomic groups[2]. Such imbalances cast doubt on the reliability of so-called 'global' summaries, which often overlook regions experiencing rapid environmental changes[21]. The paucity of detailed species distribution data, especially in under-sampled tropical areas and for invertebrates in general, hinders our ability to detect species range shifts comprehensively, identify their putative drivers and discern their consequences for global biodiversity and conservation[16,24].

To address these limitations, we focused on butterflies, which have long been used as a sentinel of change to detect comprehensive range shifts signals in response to global warming[3]. We combined systematic literature searches with the targeted extraction of evidence from non-English sources, grey literature and expert knowledge, thereby expanding distribution data coverage beyond regions and taxa that dominate conventional literature reviews. Specifically, we initiated an extensive collaborative effort to integrate existing datasets with non-traditional data sources in 15 languages and elicited 68 expert assessments. Integrating multiple types of evidence is a powerful

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Table 1 | Types and definitions of range shifts considered in this study, including examples from butterfly species

Range shift type	Definition	Example
Range expansion	The process by which a species' range expands horizontally by colonizing new locations and establishing viable populations beyond the margins of its original area of occupancy[135]. To be inclusive, we considered species new to a region as range-expanding species.	Between 2012 and 2019, *Acraea terpsicore*, native to the Indian subcontinent, expanded its geographic range at 135 km yr^{-1} in Australia[17].
Range contraction	The process by which a species' range contracts horizontally by going locally extinct (that is, extirpation) in parts of its original area of occupancy[135]. To be inclusive, we considered species that became extirpated from a region as range-contracting species.	Over the last 150 years, *Cupido minimus* has lost 40% of its habitat in the UK[136], leading to severe horizontal range contraction along the latitudinal gradient of the UK.
Elevational shift	The process by which a species moves to higher or lower elevational areas (for example, shifting its upper elevational limit, its optimum elevation or its lower elevational limit either upslope or downslope), compared to its original elevational range[7].	Between 1988 and 2011, *Vanessa cardui* experienced a range shift towards higher elevations at a rate of 83 m yr^{-1} in Mexico, while *Danaus gilippus* shifted towards lower elevations at a rate of 32 m yr^{-1} (ref. 92).

We define 'range shifts' as partial changes in species distributions along the latitudinal and longitudinal dimensions (that is, horizontal range shifts) as well as along elevational gradients (that is, vertical range shifts), rather than complete shifts of entire populations from one location to another. Here the area of occupancy is defined as the area within its 'extent of occurrence' that is occupied by a taxon, excluding cases of vagrancy[124].

approach to quantify biodiversity change, improving sampling effort and supporting a greater level of generalization across space and taxa[25,26]. We first documented and quantified species range shifts by focusing on three main types: horizontal range expansions, horizontal range contractions and elevational range shifts (Table 1). Based on these data, we further assessed the putative drivers that were reported to underpin butterfly species range shifts, as well as highlighted priorities for future research and conservation actions.

Butterflies (~19,000 species, globally) occupy diverse zoogeographic regions, elevations and habitats[27]. Their well-characterized larval host-plant associations, high sensitivity to temperature, relatively high dispersal capacity and short lifecycles, together, render them a highly effective early warning system for detecting the biological impacts of climate change[28–32]. Redistributions of butterfly species are exceptionally well-documented among insects, enabling large-scale analyses of how range shifts relate to climate and other predictors[28,33,34]. Recent work shows that responses vary markedly across taxa and regions: climatic niche breadth predicts shifts in northern Europe[35], while butterfly assemblages exhibit multidirectional shifts associated with local climate change velocities and evolutionary history in North America[36]. More broadly, climate change can reshuffle species within their climatic niches, with consequences for community composition even when species remain within their physiological limits[37].

Global research effort in documenting butterfly species range shifts

Our dataset comprises 6,182 range shift reports from 567 unique studies (Supplementary Information Sections 1 and 2) and 68 expert assessments, covering 1,758 butterfly species across 105 countries (Fig. 1a–d and Supplementary Information Section 3) from every continent where butterflies occur[27]. These reports represent 10% of the documented butterfly species (n = 19,327)[27] from six major butterfly families (Fig. 1e). We gathered records on horizontal range expansions for 1,427 species from 97 countries (Fig. 1b), horizontal range contractions for 480 species from 27 countries (Fig. 1c) and elevational range shifts for 381 species from 18 countries (Fig. 1d).

Horizontal expansions were reported across all continents, with particularly high numbers of records in the tropics (for example, Brazil and Benin) (Fig. 1b), challenging the most recent synthesis claiming little evidence for range expansions in the tropics[16]. In contrast, horizontal range contraction reports were far less common outside of Europe and North America, with the highest density of reports being concentrated in temperate countries (for example, Belgium, UK and Sweden)[38–40] (Fig. 1c). Elevational range shifts were detected across tropical, temperate and boreal regions, but almost exclusively from the Northern Hemisphere (Fig. 1d). We found substantially fewer reports of elevational range shifts in the tropics despite temperature declining faster with elevation in these regions and despite steeper adiabatic lapse rates therein, which would theoretically facilitate faster upslope redistributions in response to global warming[10,11,41].

One potential reason for the higher number of range expansion reports we found in the tropics could be the inclusion of non-English scientific literature[4,42], as well as additional records from several international experts on butterflies. To evaluate the importance of data integration from non-English-language studies and expert assessments, we compared the composition of documented range shift types across evidence sources using reference-weighted counts (that is, unique source per range shift type) (Extended Data Fig. 1). The composition of range shift types differed among the categories of sources (Pearson's χ^2 = 38.14, d.f. = 4, P < 0.001; Cramér's V = 0.161). Standardized residuals indicate that English-language sources over-represented horizontal range expansions and under-represented horizontal range contractions (expansion: 2.94; contraction: −4.14), and vice versa for expert assessments (contraction: 5.73; expansion: −4.68), while there was no difference for non-English-language studies (standardized residuals near zero). Together, these patterns indicate that reliance on English-language studies alone would bias the assembled evidence base towards a pattern dominated by horizontal range expansions, and that incorporating expert and multilingual sources reveals the broader pattern of range shift dynamics across the globe, thus strengthening inference about the diversity of redistribution responses.

There were substantial differences in the taxonomic coverage of butterfly range shift evidence. Relative to the total number of known species per family, nymphalids had the highest percentage of species shifting their ranges, while riodinids had the lowest (Fig. 1e). Relative to the total number of butterfly species for the focal family and relative to the total number of species for which we found evidence of range shifts (n = 1,758), the highest percentages were always reported for horizontal range expansions and the lowest ones for elevational range shifts (Fig. 1e). Uneven taxonomic coverage can limit the taxonomic completeness of this synthesis, because well-studied families contribute disproportionately to the available evidence, whereas low-coverage families represent important monitoring gaps in which comparable species range shifts may remain under-detected.

We found a clear imbalance regarding reporting intensity: 65% of species had a single record of range shift from a single study and country (Fig. 1a). Only 94 species (5%) had more than ten independent reports of different range shifts from at least ten different studies, with 66% of these indicating horizontal range expansion. Only three species (*Pararge aegeria*, *Lasiommata megera* and *Vanessa cardui*) had multiple records of elevational range shifts across multiple studies (Fig. 1a). For example, *Araschnia levana*, *Boloria selene* and *P. aegeria* had the highest number of records for horizontal range expansion (n = 34), contraction (n = 25) and elevational range shift (n = 6), respectively, and in many cases, these records were originating from different regions. For four species (*V. cardui*, *Nymphalis antiopa*, *Gonepteryx rhamni* and

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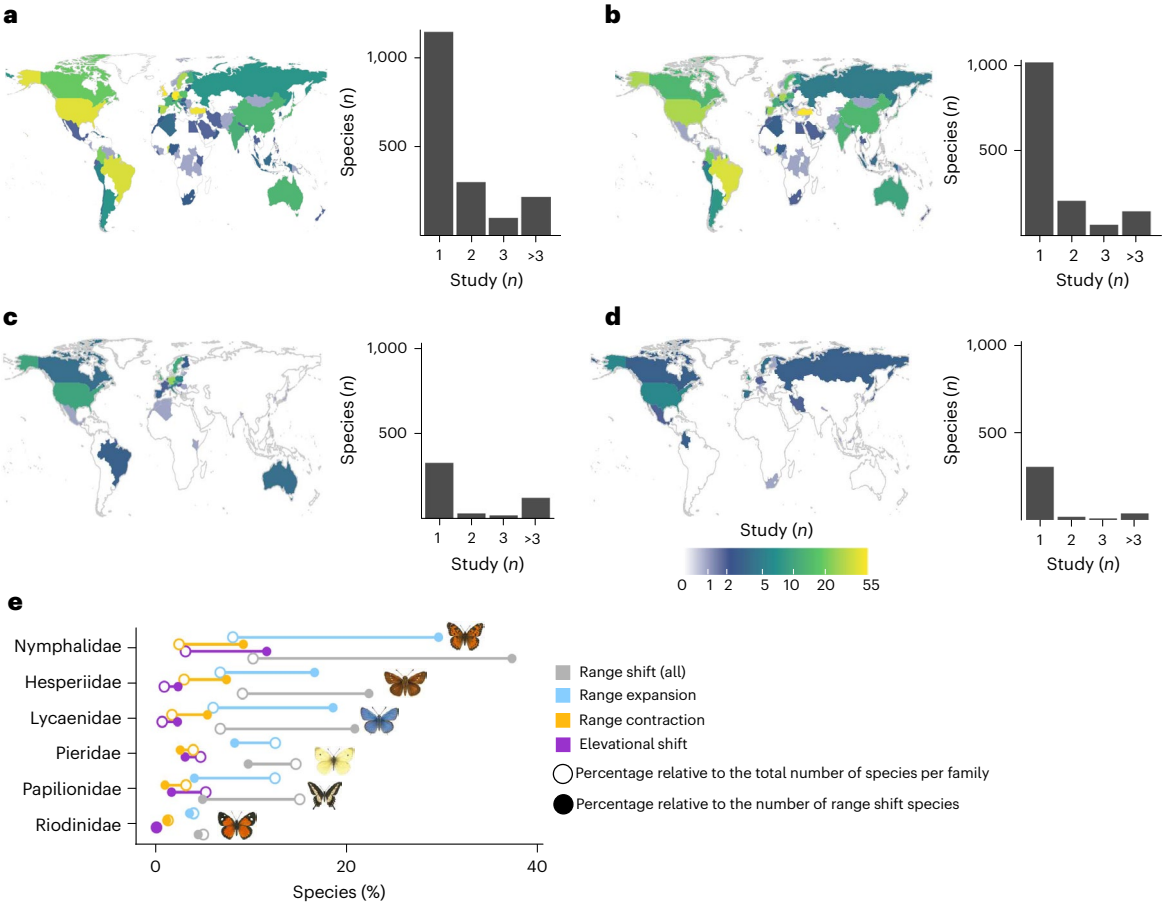

Fig. 1 | Global spatial patterns of range shift reports (n = 6,182) stemming from 567 unique studies and 68 expert assessments. a–e, The cumulative number of reports is displayed per country (**a**–**d**) as well as per family (**e**) for range shift (all) (**a**), range expansion (**b**), range contraction (**c**), elevational shift (**d**) and family-wise pattern (**e**). The colour legend on the maps at the country level (**a**–**d**), in log scale, shows the number of studies (including expert assessments) reporting range shifts for butterflies, where 0 means that we did not find any study reporting range shifts for any butterfly species within the focal country (shown in white). Histograms next to the maps depict the cumulative evidence of range shift reports, measured as the number of studies for which a given species had been reported to shift. At the family level, we calculated both (1) the percentage of butterfly species covered by our dataset relative to the total number of butterfly species known to science for the focal family (open circles) and (2) the percentage of butterfly species shifting their ranges within the focal family relative to the total number of species shifting their ranges in our dataset (n = 1,758) (closed circles).

Anthocharis cardamines), we gathered records of both upslope and downslope elevational range shifts.

Spatial patterns of butterfly species' range shifts

We detected strong geographic variation in the percentage of butterfly species shifting their ranges (Figs. 2 and 3). When considered relatively to the country-level species pool (that is, the total number of butterfly species in each country, as reported in ref. 27), five European nations (that is, the Czech Republic, Finland, Luxembourg, Spain and Sweden) dominate, each having documented records of range shifts for at least 50% of their butterfly fauna (Fig. 2). Conversely, in most countries, the documented range shifts were recorded for <10% of the national species pool. Among range shift types, Sweden had the highest taxonomic representativeness for reports on horizontal range expansion (61%), while the Czech Republic and the UK had the highest percentages of horizontal range contraction (63%) and elevational range shifts (18%), respectively. Importantly, these percentages quantify documentation coverage in our evidence database, not the absolute prevalence of range shift records across all butterflies within a country.

To better address sampling gaps, we calculated the percentage of butterfly species per country for which we have range shift data, but this time relative to the set of species that have at least one documented range shift record anywhere in our dataset (that is, species with at least one record of expansion, contraction or elevational shift in any country). For 32 countries from all six continents, at least 25% of the butterfly species have experienced a range shift, and in ten countries, this was true for >50% of the species (Fig. 3). The highest percentages appeared in the Czech Republic (84% for horizontal range expansions), Sweden (85% for horizontal range contractions) and Mexico (39% for elevational range shifts).

We then examined the composition of documented range shift types to avoid conflating differences in the volume of evidence with differences in range shifts. Across continents, horizontal range expansions were the most frequently documented range shift type, whereas the proportional contributions of horizontal range contractions and elevational range shifts varied among regions. In total, 77% of species (1,349 species) had records for a single type of range shift in our dataset—typically horizontal range expansions (76% of 1,349 species). However, 409 species (23%), especially in Europe and parts of South America, had records covering multiple range shift types, such as both horizontal range expansions and contractions, either within a country or across different countries. For example, *Aporia crataegi* experienced both horizontal range expansion and contraction in Andorra. These multidimensional shifts highlight the complexity of biotic responses to ongoing environmental pressures and underscore the importance of distinguishing among different types of range shifts when assessing biodiversity redistribution[9].

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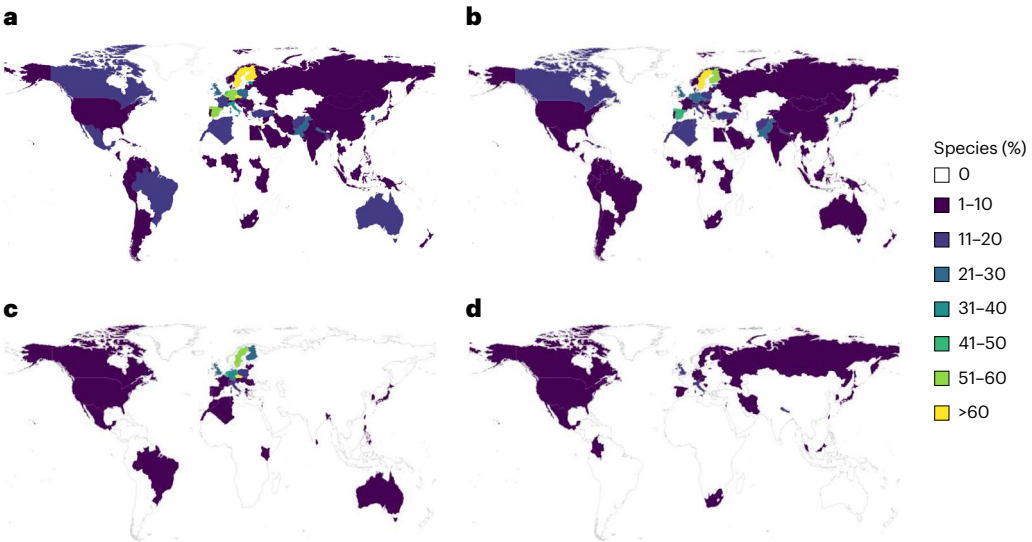

Fig. 2 | National prevalence of documented butterfly range shifts relative to species richness. a–**d**, Proportion of range-shifting species within each country relative to the total number of butterfly species known to occur within the focal country[27], for all range shifts (**a**), range expansion (**b**), range contraction (**c**) and elevational shift (**d**), with 0% indicating that we did not obtain any range shift data from the focal country (shown in white). High values in Europe reflect both genuine change and the much greater probability of detecting range shifts given long-term programmes; lower values in many tropical countries likely reflect data scarcity rather than the absence of range shifts for butterfly species.

We used a centroid-based approach to allocate each country to three groups (Europe, the tropics, and non-European countries and non-tropical countries). Because several large countries (for example, the USA and Australia) span both tropical and temperate zones, we classified them following our regional groupings; for example, the USA was allocated to the non-European and non-tropical countries group. Range shift type composition differed strongly among the three regions (Pearson's $\chi^2 = 389.13$, d.f. = 4, $P < 0.001$; Cramér's $V = 0.277$), driven by an over-representation of horizontal range expansions in the tropics and higher relative representation of horizontal range contractions and elevational range shifts in Europe. In Europe, documented records were relatively balanced across horizontal range expansions (41.3%), horizontal range contractions (37.4%) and elevational range shifts (21.3%). By contrast, horizontal range expansions dominated in the tropics (80.3%) and in non-European and non-tropical countries (64.8%) (Extended Data Fig. 2). Importantly, elevational range shifts were rarely documented in tropical countries, highlighting the need for integrated monitoring approaches that improve detection of under-represented range shift types in some regions, like elevational range shifts in tropical countries.

To assess sensitivity to a potential publication bias (for example, the tendency for references of single-species range shifts to be more frequently reported in the scientific literature), we repeated the continental summaries using a reference-weighted approach (that is, each reference counted once per range shift type) and restricted the analysis to multi-species references (≥2 species per reference). Patterns were broadly consistent, with horizontal range expansions remaining the most commonly reported type of range shifts across continents. However, in the multi-species subset, the relative contribution of horizontal range contractions increased in some regions (for example, expansions dropped from 0.93 to 0.73 in Africa, and contractions increased from 0.3 to 0.36 in Europe; Extended Data Fig. 3). These results support interpreting our findings as relative patterns within our dataset rather than as absolute rates of change. Future studies could conduct a targeted meta-analysis of range shift magnitude for studies reporting compatible quantitative outcomes (that is, standardized range shift rates and uncertainties, which we were not able to compile here).

We pinpoint where and how butterfly ranges are changing globally and highlight the urgent need for equitable and standardized monitoring. Despite representing a vast portion of the world's butterfly diversity, regions such as Central Africa, Southeast Asia, mainland New Guinea and its surrounding islands, and the Amazon Basin remain markedly under-represented. This is also the case in our current and, to our knowledge, largest effort to compile records of range shifts for butterflies, leveraging both expert assessments and studies across 15 languages. An important note is that in many tropical studies, range shifts were recorded simply as local fluctuations of population sizes or local population appearances and disappearances, rather than quantified using standardized analyses of range shift rates (Table 1), highlighting that despite our efforts adequate detection and reporting is scarce outside of Europe. This is worrying because tropical species are especially vulnerable—they already live near their upper thermal limits, have restricted distribution ranges and often a narrow thermal flexibility range, and are isolated from cool refugia[39,43,44]. However, the tropics are not warming as fast as temperate areas, which could limit the number of range shift reports of butterfly species from the tropics. Our results contradict reports that elevational range shifts are also more commonly reported for tropical insects than poleward range shifts[16,45]. A recent global analysis suggests a major erosion of the future geographical extent suitable for butterfly species according to their thermal niches, with up to a 64% loss projected by 2100, even when assuming full dispersal within biogeographical realms[46]. This implies major range contractions and particular vulnerability of rare tropical species at higher elevations.

Drivers of butterfly range shifts

We compiled threat data reported to be linked to butterfly range shifts by extracting the putative drivers identified in the studies or by experts across 68 countries. For example, *Boloria aquilonaris* has lost much of its original habitat in Germany due to bog drainage (that is, habitat loss and degradation)[47], while in Romania, habitat homogenization and agricultural intensification caused a severe range contraction for *Colias myrmidone*[48]. In Brazil, *Godartiana byses* has expanded its horizontal range from the states of Rio de Janeiro and Bahia to São Paulo in response to climate warming[49]. Biological invasions also explain range shifts for some of the studied butterfly species. For instance, the introduction of *Pieris rapae* led to dramatic range contractions of *Pieris oleracea* in the USA[50].

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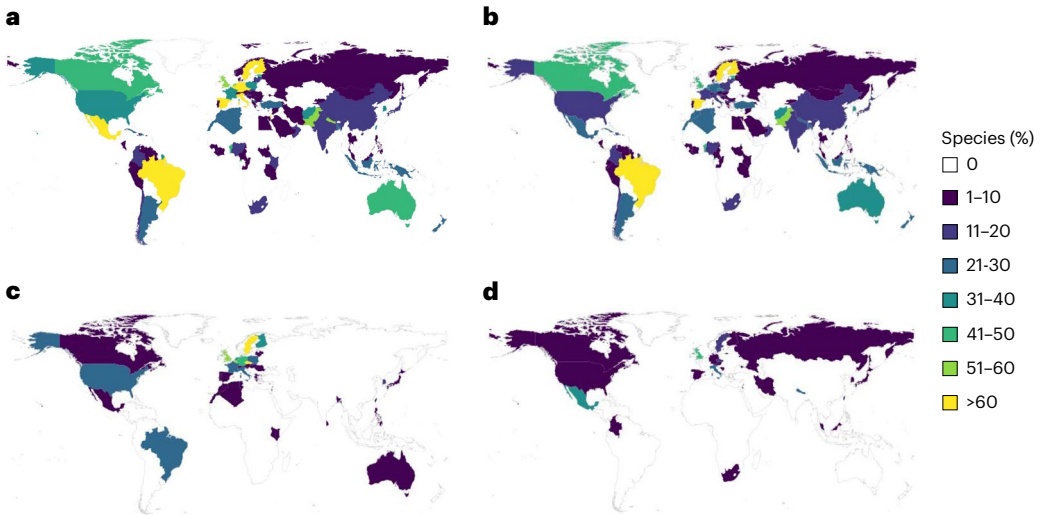

Fig. 3 | National representation of butterfly species documented as range shifting globally. a–d, Proportion of range-shifting species within each country relative to the total number of range-shifting species that were reported to have experienced range shifts either in the focal country or elsewhere across our dataset (all range shifts (**a**), range expansion (**b**), range contraction (**c**) and elevational shift (**d**)), with 0% indicating we did not obtain any range shift data of any butterfly species in the focal country (shown in white). High values in Europe reflect both genuine change and the much greater probability of detecting it given long-term programmes; lower values in many tropical countries likely reflect data scarcity rather than the absence of range shifts for butterfly species.

We categorized the putative drivers following the International Union for Conservation of Nature (IUCN) threat categories (Methods). Overall, we identified nine primary threats that were directly or indirectly related to butterfly range shifts. Across studies, the threat entitled 'climate change and severe weather' was the most frequently reported category for butterfly range shifts (278 of 352 species with threat data), while 'energy production and mining' was the least reported category (three species only; Fig. 4a). Because most studies did not estimate comparable multi-driver effect sizes, these results summarize the prevalence of reported attributions rather than the magnitude of impact or causal dominance. 'Climate change and severe weather' was reportedly associated with the horizontal range expansions of 163 species, the horizontal range contractions of 131 species and the elevational range shifts of 61 species (Fig. 4a). The relative reporting rates of different threat categories varied across range shift types. While 'human intrusions and disturbance' and 'agriculture and aquaculture' were the most frequently reported threat categories associated with horizontal range contractions (for 143 species), 'climate change and severe weather' was the most frequently reported threat linked to horizontal range expansions and elevational range shifts (163 and 61 species, respectively). Elevational range shifts are particularly important as butterfly species richness, endemism and phylogenetic diversity are highly clustered in mountainous regions worldwide. Approximately two-thirds of all butterfly species are primarily mountain-dwelling species, but mountain climates are rapidly eroding in the face of climate change[46].

In most continents, 'climate change and severe weather' was the most frequently reported threat, whereas 'residential and commercial development', as well as 'invasive and other problematic species, genes and diseases', were the most prevalent in Oceania, and 'human intrusions and disturbance' was dominant for South America (Fig. 4b). 'Climate change and severe weather' was consistently linked to horizontal range expansions in all continents, while several other threats were linked to horizontal range contractions in different continents (Fig. 4b). Whilst there were one or two major threats in most continents, in Europe, several threats concurrently impacted horizontal range expansions and contractions (Fig. 4b).

These patterns may reflect both ecological differences and differential measurability and study emphasis among drivers (for example, climate covariates are often more readily available than local pollution or fine-scale habitat degradation). However, an effort-adjusted sensitivity analysis produced qualitatively similar driver patterns to those based on raw counts, for both species-weighted and reference-weighted summaries (Extended Data Fig. 4). Overall, 'climate change and severe weather' is the most frequently reported threat category linked to butterfly range shifts in our database, and this ranking is robust when normalizing for differences in the number of threat categories reported per reference. Where rankings differed between summaries, the differences reflected whether a threat was concentrated in a small number of species-rich references or distributed broadly across references.

Our results highlight diverse pressures and the need for region-specific conservation interventions. Species experiencing both horizontal range expansions and local adjustments through elevational range shifts may require improved population connectivity—a direct action in the 'resist–accept–direct' framework[51]—whereas contracting species may benefit from targeted protection and restoration—resist actions[52–54]. Range expansions are often associated with rising temperatures, requiring cold-limited species to colonize higher latitudes or elevations. Conversely, range contractions are typically linked to land-use changes, especially habitat loss, with species unable to persist in increasingly modified environments. Threat impacts are often population-specific and strongest near range margins where physiological limits are approached[55]. Future work could combine standardized climate metrics (for example, regional warming rates or climate change velocities) and land-cover metrics to estimate the magnitude of range shifts and test whether the direction and rate of change align with regional exposure to environmental change.

Minimizing drivers of range shifts to mitigate butterfly decline

Our dataset confirms findings from pioneering studies on species range shifts, that butterflies tend to expand more than they contract their ranges[3,8]. This is likely due to their phenotypic plasticity, which allows local populations to survive in areas near the range margin by adopting opportunistic or behavioural strategies[55–57]. The fact that many species in our dataset exhibit only one range shift type, whereas a minority shows multiple range shift types across regions, further emphasizes that species redistribution can be multidirectional and context-dependent rather than uniformly poleward and upslope.

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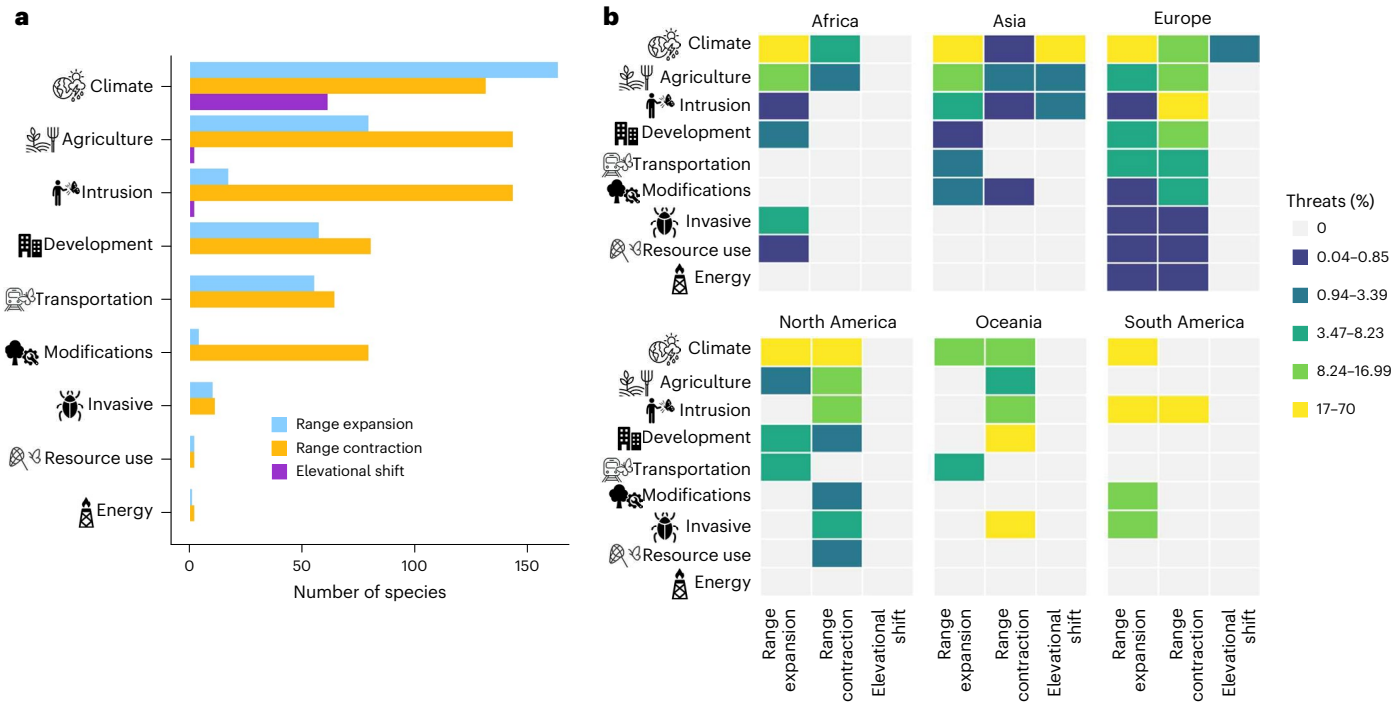

Fig. 4 | Distribution of threats attributed to butterfly species' range shifts (compiled from published literature and experts' knowledge). a, Summary of the identified threats underlying butterfly species range shifts, where each bar shows the number of butterfly species for which range shifts were attributed to a given threat. **b**, Distribution of threats per continent. 'Threats (%)' indicates the percentage of times the threat was reported in a given species-by-continent combination. 'Agriculture', agriculture and aquaculture; 'climate', climate change and severe weather; 'development', residential and commercial development; 'energy', energy production and mining; 'intrusion', human intrusions and disturbance; 'invasive', invasive and other problematic species, genes and diseases; 'modifications', natural system modifications; 'resource use', biological resource use; 'transportation', transportation and service corridors.

The different types of threats reported in the scientific literature also suggest that biodiversity redistribution is constrained as much by landscape context as by climate change exposure. Range shifts in butterflies can be restricted by host-plant availability, habitat fragmentation or limited dispersal across islands and mountain tops[3,58,59]. Habitat heterogeneity is, therefore, crucial to provide refugia and buffer populations against abrupt losses[60,61]. In practice, this means that even where climate becomes suitable, colonization may fail if host plants and suitable microclimates are absent or if habitat connectivity is insufficient to bridge distant and isolated habitat patches.

Climate change mitigation remains central to minimizing the climatic debt—the lag between shifting isotherms and population responses. Even small temperature increases may exceed physiological limits, alter seasonal phenology or disrupt biotic interactions with host plants and mutualists[31,62,63]. For example, with rising temperatures, Scandinavian butterflies have expanded northwards[30,64], whereas alpine species are being squeezed towards mountain tops[65]. Limiting global warming will be crucial for maintaining accessibility to thermally suitable habitats and avoiding range shift gaps[45]. Across Europe and South America, butterflies retreat to shaded or forested areas on hot days[55,66–68], highlighting the role of microrefugia. Because the goal of holding global temperature increase below 2 °C, while pursuing efforts to limit warming to 1.5 °C, as established in the Paris Agreement, is becoming increasingly unachievable[69,70], conservation must pair mitigation with adaptation—such as protecting microrefugia[71], buffering habitat edges and improving landscape connectivity—to build resilience[53,72,73].

Equally important is the protection and restoration of habitat quality. Land-use change—including agriculture, aquaculture and urban development—is a leading cause of horizontal range contractions in butterflies[38,74,75] (Fig. 4). Habitat degradation decreases the availability of crucial host plants, nectar sources and microclimates necessary for butterfly survival[76,77]. Protecting intact habitat patches, restoring degraded habitats and connecting isolated habitat patches can enable recolonization and sustain genetic diversity[29,78–81]. Even small, well-managed habitat patches enhance metapopulation persistence when total habitat amount is sufficient[59,81].

Other anthropogenic pressures, such as urbanization, roads, invasive species and chemical use, further restrict movement and degrade habitats[17,78,79,82–85]. Integrating biodiversity goals into infrastructure and land-use planning—through ecological corridors, stepping stones and robust environmental assessments—can sustain habitat connectivity[52,81]. Because these pressures often co-occur and can interact with global warming[86], future studies could prioritize multi-driver designs that quantify the relative contributions of climate change exposure and landscape constraints (for example, habitat fragmentation, host-plant loss, pollutants) using comparable metrics of range-edge change over time.

Finally, building ecological resilience is essential for long-term stability[87]. Diverse, structurally complex ecosystems can better withstand disturbance and maintain genetically robust butterfly populations. Conserving diverse populations and their biotic interactions lowers the risk of range contractions while facilitating adaptive shifts[79,88,89]. In the Brazilian Atlantic Forest, landscape composition and configuration were as important as climate in shaping local butterfly diversity, with forest loss posing the greatest threat[90].

Overall, our synthesis indicates that biological conservation for butterflies that are already shifting their ranges requires two interconnected strategies: (1) reducing exposure to major drivers (for example, climate and land-use change) and (2) maintaining the ecological and landscape conditions that enable local populations to persist and move (for example, host plants, microrefugia and habitat connectivity). Minimizing these threats requires an integrated approach that links climate mitigation, habitat protection, sustainable land management

and coherent policy action to prevent biodiversity loss in a rapidly changing world.

Future monitoring and conservation prospects

Geographic and taxonomic biases strongly influence biodiversity assessments and conservation strategies[21,32,91]. The apparent dominance of reports on horizontal range expansions might be partly influenced by detection and reporting biases rather than by actual ecological trends. Our semi-quantitative synthesis, therefore, highlights a dual challenge: (1) closing spatial and taxonomic gaps in baseline monitoring and (2) improving how heterogeneous evidence (including citizen science and local knowledge) is validated, standardized and integrated so it can support robust inference and conservation action. If horizontal range contractions and elevational range shifts are not adequately documented in tropical regions—where the impacts of climate change and land-use pressures are very severe—we would greatly underestimate the vulnerability of tropical butterflies[15,16,92,93].

To close this gap and advance the field, we propose a three-fold applied framework: (1) expanding monitoring programmes in under-represented regions; (2) integrating citizen science and local knowledge; and (3) accounting for species range shifts in conservation planning.

Expanding monitoring programmes in under-represented regions

Long-term monitoring in Europe and North America has revolutionized our understanding of butterfly responses to environmental changes (for example, refs. 94–96). However, such programmes are scarce in the tropics and arid and semi-arid regions[32,93,97], limiting our understanding of species responses to global change[98]. For one third of all butterfly species, not even a single occurrence record is currently available[46]. Priority expansion of monitoring should, therefore, target (1) biodiversity hotspots and endemism centres, (2) elevational gradients and (3) regions identified here as evidence-poor, supported by international collaboration and local capacity building[4,21,99–101]. Digitizing museum and private collections can recover historical data and extend temporal coverage[60,102], while including local-language and non-indexed publications can reduce geographic bias and improve the spatiotemporal coverage on species distribution data. These efforts will help reconstruct historical range boundaries and bridge spatial and temporal data gaps.

Integrating citizen science data and local knowledge

Citizen science platforms such as iNaturalist and national biodiversity portals have rapidly expanded biodiversity occurrence data, but remain geographically skewed[4,103,104]. Community-led initiatives, coupled with emerging technologies (for example, social media platforms) and local partnerships can improve data validation and coverage[4,103,105–108], with examples from Brazil[109,110], Bangladesh[15,111] and the Philippines[112]. For instance, using the *Acraea terpsicore* butterfly, a recent study found that integrating species locality records from social media with records from the biodiversity database can track expansion much more effectively, identifying new distributions from the tropics, especially from high-elevation areas[113]. However, these data are often opportunistic and heterogeneous in sampling effort, making them difficult to use alone for robust inference about temporal trends, the rate of range change or the mechanisms underpinning species range shifts. For this, citizen science is most powerful when paired with structured monitoring (first step)—standardized protocols provide consistent effort through time and space, improving range shift detectability, and generating comparable baselines against which opportunistic observations can be calibrated[4,114].

These examples demonstrate a huge untapped potential, but also highlight the need to explore alternative and complementary monitoring approaches. This could possibly be achieved through a combination of structured transect walks, time-bound counts and fruit baits for forest areas, but other approaches may need to be explored. Incentivizing participation through recognition or microgrants can further boost engagement[115,116]. Embedding citizen science in national biodiversity strategies will help track progress towards post-2020 Global Biodiversity Framework targets and enhance conservation literacy[117–119].

Accounting for species range shifts in conservation planning

Despite mounting evidence of species range shifts, conservation frameworks rarely consider range dynamics when delineating protected areas, limiting their applicability and ability to protect biodiversity under climate change. While protected areas have been established to insulate species from various direct threats[120,121], 76% of insect species are inadequately represented within the current protected area system[122]. The situation is worse for migratory butterfly species, with 85% being inadequately protected[123]. We show that both horizontal range contractions and elevational range shifts are under-documented in many regions, yet these range shift types are the most immediately relevant for extinction risks and protected area adequacy. To address these limitations, conservation planning should incorporate real-time species range shift data[39,124]. Aligning national efforts with the Kunming–Montreal Global Biodiversity Framework will require systematically incorporating range shift data into better informed spatial planning, monitoring and progress reporting[125,126]. Existing tools such as the IUCN Red List rely on static maps, with most threatened insects listed under restricted-range criteria (B or D2) rather than population decline (A)[127].

Species facing horizontal range contractions or elevational range shifts need targeted interventions, such as maintaining elevational connectivity, restoring refugia or establishing transboundary corridors. Lastly, scenario-based forecasting using species distribution models can be a powerful tool for proactive conservation planning, especially so for data-poor species or for tracking species niche, assessing species vulnerability to global change, prioritizing future conservation areas, restoring stepping-stone habitats or establishing transboundary agreements for migratory or shifting species[128–130].

Ultimately, conservation needs to shift from reactive to adaptive approaches, adopting predictive modelling and including species range dynamics in policy and practice.

Conclusion

Butterflies are a highly diverse and widely distributed species group, contributing to many ecosystem services and serving as a sentinel of change[32,131]. We report that, globally, current knowledge on butterfly species' range shifts covers only one in ten species, often involving 'climate change and extreme weather', along with 'agriculture and aquaculture' and 'human intrusions and disturbance' as the most likely drivers of butterfly redistribution. Despite our efforts to build the largest dataset compiling reports of range shifts in butterflies, our understanding of how butterflies respond to global changes remains biased towards temperate species, with many species, especially in the tropics, lacking detailed data. Expanding biodiversity monitoring, including citizen science approaches and accounting for range dynamics in conservation, will enhance our understanding of butterfly responses to environmental change and aid in developing more adaptive, forward-looking conservation strategies. Without such global, co-ordinated efforts, we risk missing the early warning signals of biodiversity collapse, especially in regions and for taxa that are under-represented in existing data repositories. Considering that many other taxa are experiencing similar shifts in their geographic ranges, our methods and recommendations are transferable to other taxonomic groups and scalable across terrestrial and marine realms to understand how biodiversity responds to global change drivers and, thus, work jointly towards effective conservation and restoration.

Methods

We followed two primary steps to extract data on butterfly species range shifts. First, we reviewed the published scientific literature. Then, to account for the widely acknowledged bias in the published scientific literature, we invited 68 butterfly experts, all co-authors, from 49 countries to fill this knowledge gap.

Many authors publish their research in regional journals and in non-English languages, and these studies are largely unavailable in the international search systems, such as Web of Science[42,132]. For this, we searched for published literature in 15 languages (Supplementary Information Section 1 and Extended Data Fig. 5). For English-language studies, we used Web of Science and Google Scholar, while for studies published in non-English languages, we used Google Scholar and local search systems available within the focal country. For both English and non-English-language studies, we restricted our search to 1991 onwards, as our understanding of butterfly species distribution was more limited and very scattered before the 1990s.

We started our search using the Web of Science (using the University of Queensland IP address; Core Collection with KCI (Korean Journal Database), MEDLINE, Preprint Citation Index and SciELO Citation Index). We filtered literature using the following Web of Science categories: Ecology, Entomology, Biodiversity Conservation, Evolutionary Biology, Zoology, Environmental Sciences, Multidisciplinary Sciences, Plant Sciences, Biology, Biochemistry, Molecular Biology, Genetics, Heredity, Behavioural Sciences, Forestry, Agronomy, Environmental Studies, Developmental Biology, Urban Studies, Geography and Remote Sensing. Overall, we obtained 5,498 studies from the Web of Science.

We further explored relevant studies using Google Scholar. We used seven keywords and for each search keyword, we reviewed the first 200 articles filtered by relevance (20 pages, with 10 articles on each page; Supplementary Information Section 1). As we searched for non-English-language studies separately, we restricted our search to English-language studies. We downloaded the HTML pages of the search results for each keyword and used the 'litsearchr' R package[133] to extract publication information for all 1,400 studies. We used Rayyan (https://rayyan.ai/)[134] to screen the titles and abstracts. We uploaded all studies obtained from both Web of Science and Google Scholar to Rayyan, totalling 6,898 studies.

We followed two steps when searching for literature in non-English languages. For Google Scholar, we translated English keywords, restricted the language and searched for relevant studies (Supplementary Information Section 1). Similar to English-language literature, we considered the published literature between 1991 and 2022, as well as the first 200 articles (up to 20 pages).

Given that many non-English-language studies are not available in international search systems[42], we further explored language-specific search systems. Here we translated English keywords and searched for relevant studies in language-specific search systems, if available (Supplementary Information Section 1).

To include or exclude a paper, we read the title and abstract of each paper. We excluded papers if we could not find any information about changes in the geographic range of butterflies. We also excluded papers if the authors discussed range shifts from a metapopulation perspective (that is, from one patch to another), if the paper focused on future range shifts (that is, predicted changes in suitability) or if the paper discussed postglacial range expansion (Extended Data Fig. 5).

From each study, we extracted the publication information (for example, journal, DOI), taxonomic details (for example, species), geographic information (for example, country), type of range shift (for example, horizontal range expansion, horizontal range contraction or elevational range shift), the potential drivers behind the reported range shifts (as stated by the authors), whether the species is invasive, the impact on native species and whether the species is facing any threat. We used countries as observational units because most sources report species range shifts at the national level (atlases, checklists, expert assessments) and because national baselines are required for conservation reporting and resource allocation.

We contacted the IUCN Species Survival Commission Butterfly and Moth Specialist group and the Butterfly Conservation group to compile a list of butterfly experts that we contacted and who have been conducting fieldwork for many years. Once each expert agreed, we asked them to provide independent assessments of range shift information for the species and regions with which they were directly familiar. We used the same standardized template form to extract information from published studies and expert assessments. Specifically, experts classified their records according to the same three range shift categories used throughout the study—horizontal range expansion, horizontal range contraction and elevational range shift (Table 1)—based on their field observations and associated knowledge of species' occurrence and change through time. These expert assessments were treated as an additional evidence stream alongside the published literature, rather than as a validation step for studies extracted by other data extractors. Where possible, experts used changes in documented area of occupancy through time, based on field observations and local distribution knowledge, to determine whether a species had changed its range and, if so, which of the three range shift types best described that change. Future research efforts will focus on collecting raw distribution data to better quantify the magnitude and direction of range shift rates in butterflies.

We aggregated both the datasets from published studies and expert assessments to understand the global patterns of range shifts in butterflies. Finally, we used the most comprehensive and recent taxonomy of butterflies[27] to match range shift information and country-level distribution data. The total count of species per family based on this source was as follows: 6,387 species of Nymphalidae, 5,364 species of Lycaenidae, 4,290 species of Hesperiidae, 1,571 species of Riodinidae, 1,165 species of Pieridae and 580 species of Papilionidae, respectively. For our analysis, we excluded Hedylidae (37 species)—American moth-butterflies—whose taxonomic status has long been debated, traditionally leading to their omission from butterfly literature.

Once the data collection was completed, we computed the cumulative sum of reports on range shifts for each country, species and range shift type separately for the published studies and the expert assessments, to understand the global patterns of range shifts in butterflies. We categorized threats using the IUCN Threats Classification Scheme (version 3.3; https://www.iucnredlist.org/resources/threat-classification-scheme). Finally, we used the most comprehensive and recent butterfly taxonomy[27] to harmonize species names across our range shift records and the external country-level distribution dataset used to estimate national species pools. Each range shift record was assigned only to the country explicitly reported in the original study or expert assessment.

To quantify whether all 6,182 reported range shifts differed across regions, we extracted the country's centroid and grouped countries into three groups according to the country's centroid location: Europe, the tropics, and non-European countries and non-tropical countries. Because most studies did not estimate comparable multi-driver effect sizes (and many did not evaluate multiple drivers simultaneously), we summarized drivers as the prevalence of reported attributions rather than impact magnitude. To assess whether patterns could reflect differences in the breadth of reported drivers, we performed an effort-adjusted sensitivity analysis in which each study's driver attributions were weighted by the inverse of the number of distinct threat categories reported in that study. We reported results (Extended Data Fig. 4) using (1) a species-weighted summary (reference × species × threat) and (2) a reference-weighted summary (reference × threat), to evaluate the influence of references with a higher number of reports from multiple species.

Reporting summary

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

Data availability

We have provided all relevant files as Extended Data Figs. 1–5 and Supplementary Information, including search details (Supplementary Information Section 1), the list of reviewed studies (Supplementary Information Section 2) and the list of species for which we obtained butterfly range shift data (Supplementary Information Section 3).

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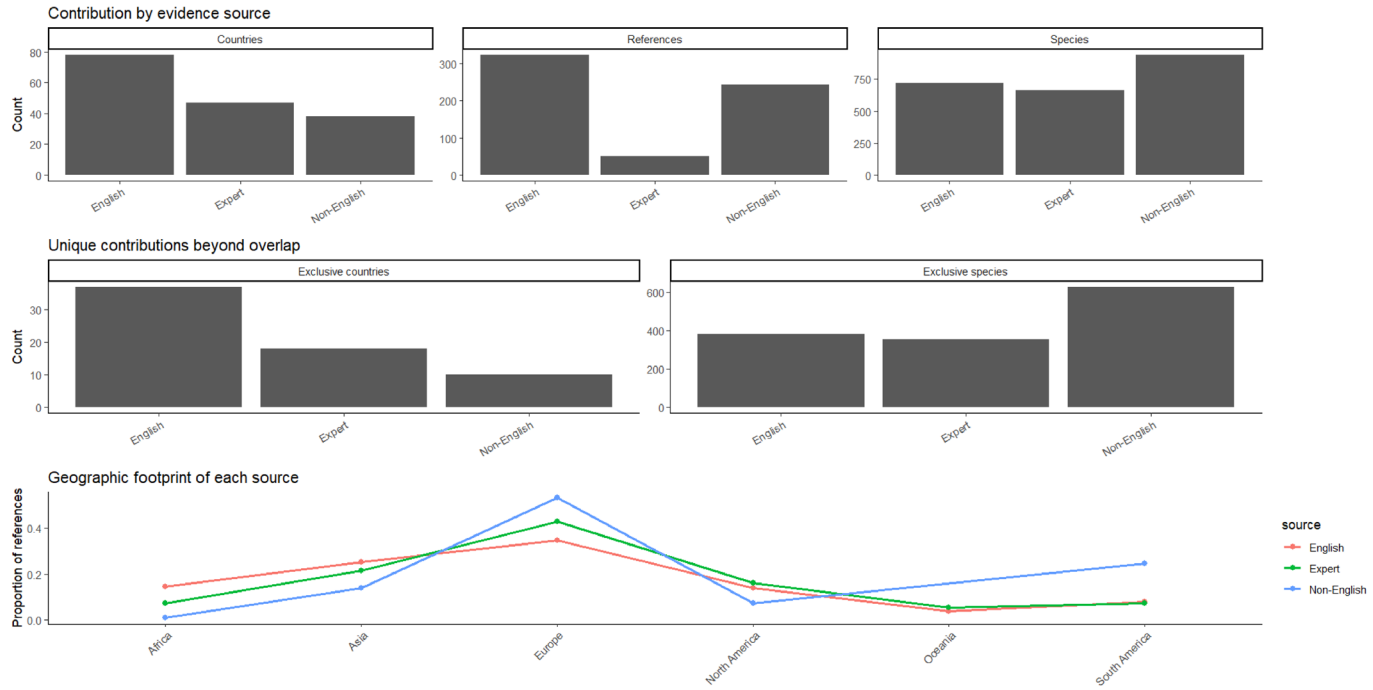

Extended Data Fig. 1 | The contribution from the data source to studying the butterfly range shift. Numbers of countries, references and species represented by English-language studies, expert assessments and non-English-language studies; their unique contributions; and the geographic distribution of references from each source.

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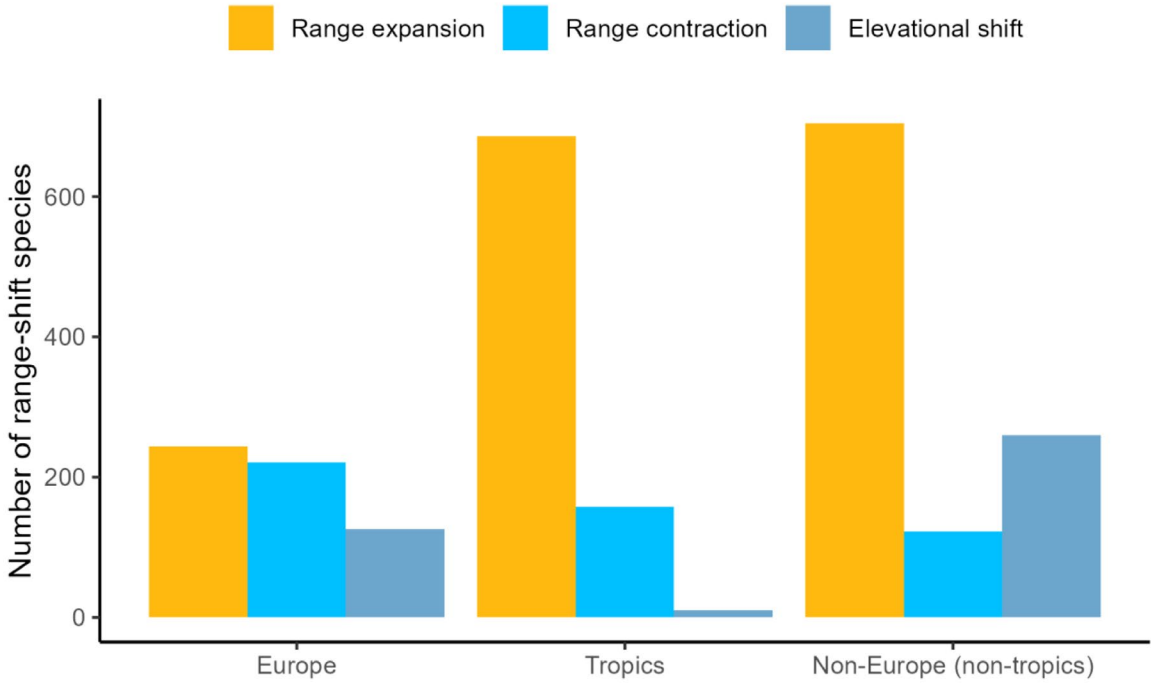

Extended Data Fig. 2 | Regional variation in butterfly range-shift types. Numbers of species undergoing range expansion, range contraction or elevational shift in Europe, the tropics, and non-European and non-tropical regions.

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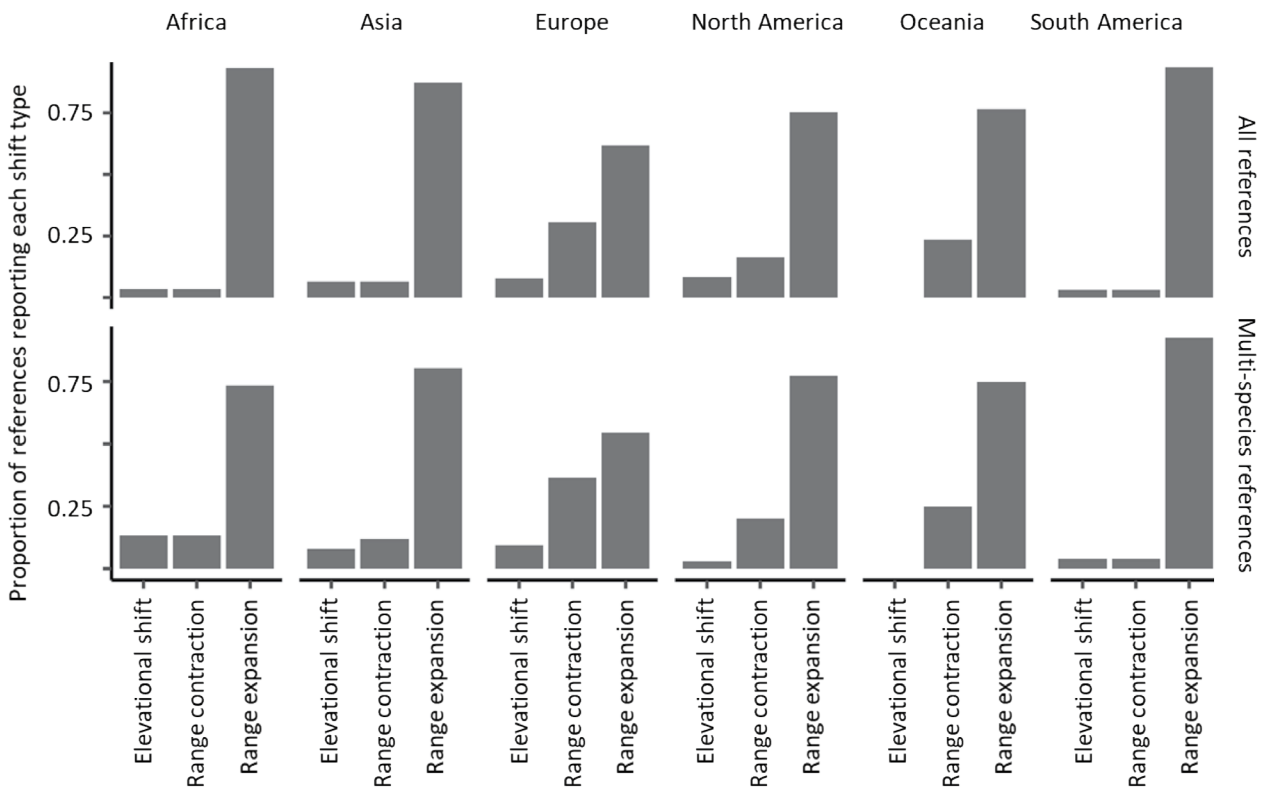

Extended Data Fig. 3 | Sensitivity of reported range shifts to reference weighting and study scope. Proportions of all references (upper row) and multi-species references (lower row) reporting elevational shifts, range contractions and range expansions in each continent.

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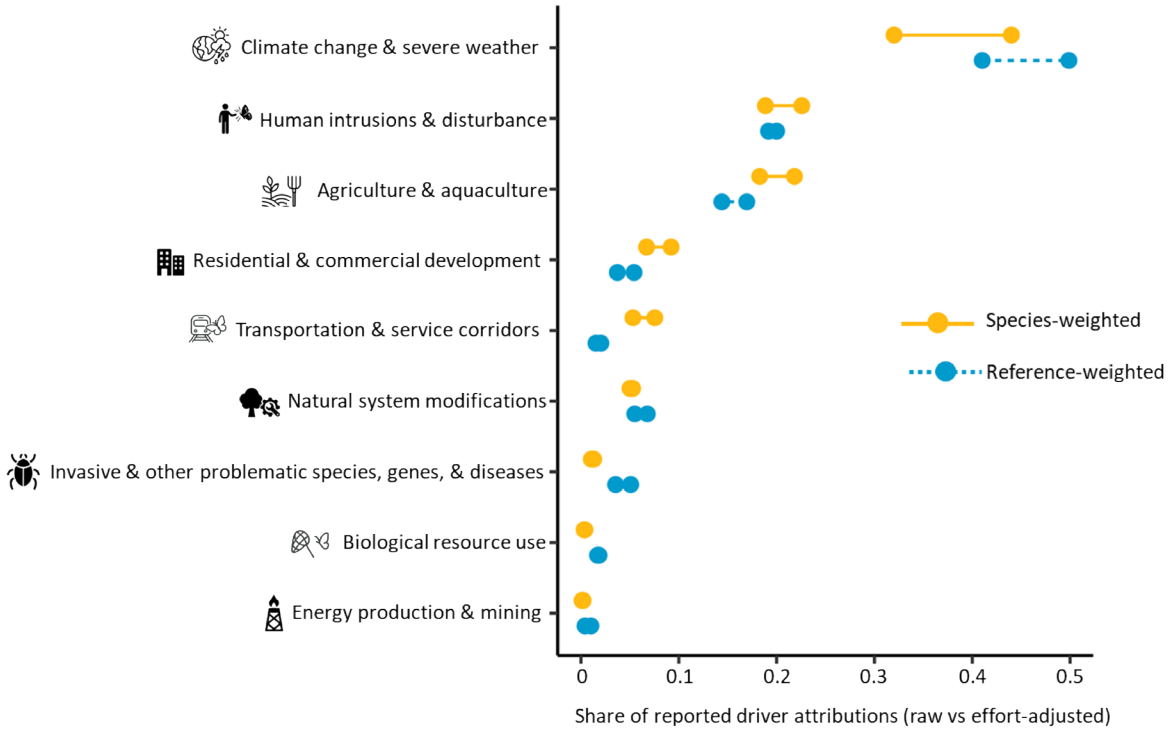

Extended Data Fig. 4 | Reporting-breadth sensitivity of inferred drivers of butterfly range shifts. Raw and effort-adjusted shares of driver attributions calculated using species-weighted and reference-weighted approaches.

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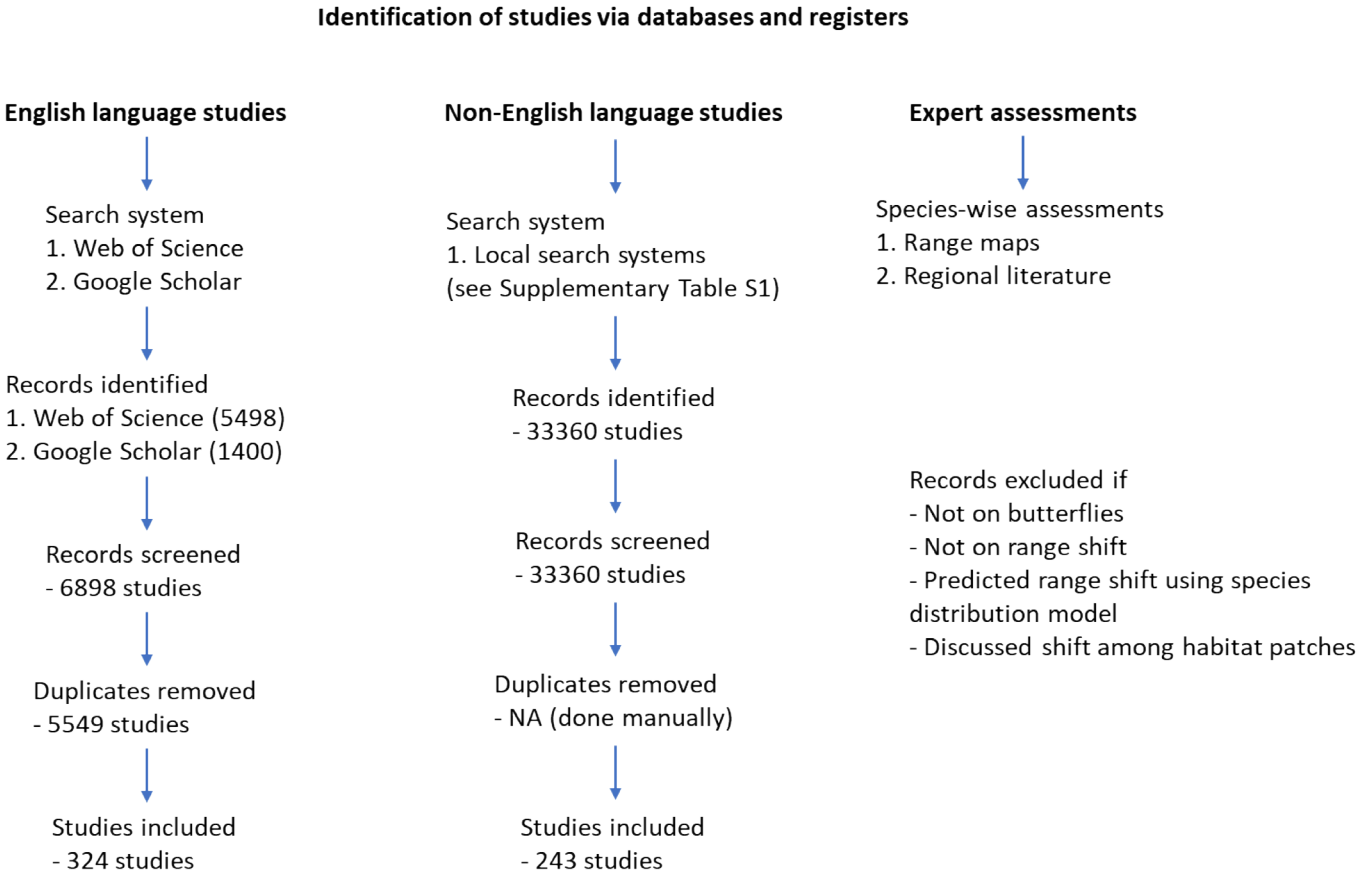

Extended Data Fig. 5 | Identification and screening of evidence on butterfly range shifts. Workflow for identifying, screening and including English-language studies, non-English-language studies and expert assessments.

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Ecological, evolutionary & environmental sciences study design

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Study description	We compiled range shift data in 15 languages and with expert assessments.
Research sample	We focus on three main types of range shifts: horizontal range expansion, horizontal range contraction, and elevational range shifts. We first document these range shift patterns before assessing which threats underpin butterfly species range shifts. Finally, we highlight priorities for future research and conservation.
Sampling strategy	NA
Data collection	We followed two primary steps to extract data on butterfly species range shifts. First, we reviewed the published literature. Then, to account for the widely acknowledged bias in the published literature, we invited 68 butterfly experts, all co-authors, from 49 countries to fill this knowledge gap.
Timing and spatial scale	1991-2022; Global (country-wise)
Data exclusions	NA
Reproducibility	We provide adequate details (e.g., literature search in multiple languages, details on non-English search systems, species list) to reproduce our findings.
Randomization	NA
Blinding	NA

Did the study involve field work? ☐ Yes ☒ No

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☒	☐ Plants

Methods

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

Plants

Seed stocks	NA
Novel plant genotypes	NA
Authentication	NA