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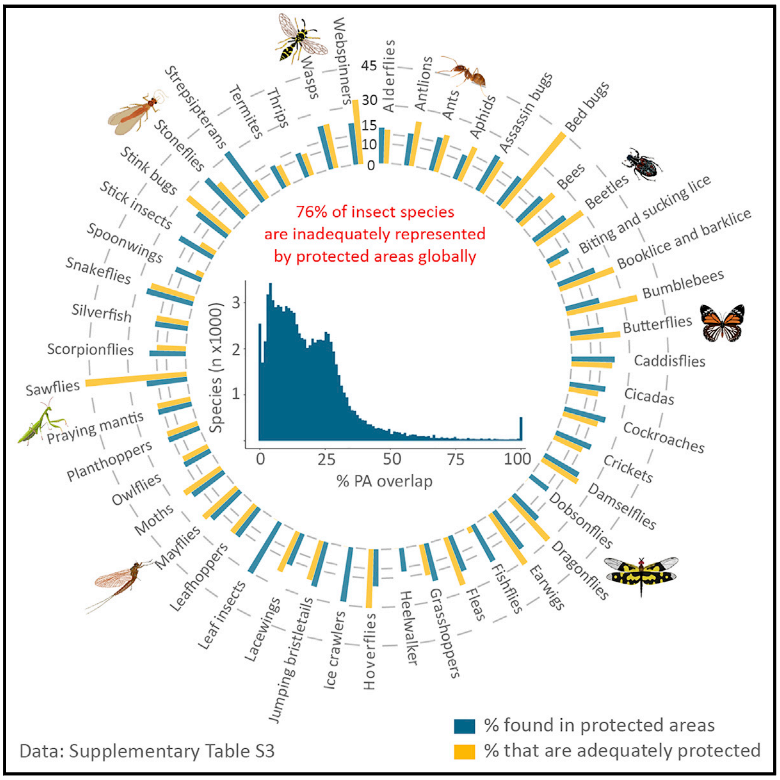
Article

Three-quarters of insect species are insufficiently represented by protected areas

Graphical abstract



Highlights

- Mean PA coverage across all insect species is 19%
- About 76% of insects do not meet minimum PA target coverage
- Nearly 2% of insects do not overlap at all with PAs

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In brief

Insects are central to ecosystem functioning yet are often neglected in large-scale conservation assessments. While protected areas (PAs) have become a critical conservation tool, no study has assessed the performance of PAs in insect conservation globally. Using a widely accepted method, we show that >75% of insect species are inadequately represented by PAs globally and that 2% of insect species are not covered by any PAs. Explicit inclusion of insects in systematic conservation planning is essential to halt widespread insect declines.

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One Earth

CellPress

Article

Three-quarters of insect species are insufficiently represented by protected areas

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SCIENCE FOR SOCIETY Insects are declining in many parts of the world, yet they constitute only 8% of the assessed species in the IUCN Red List. While protected areas (PAs) could play a key role in safeguarding many insect species from extinction, coverage of insect distributions by PAs remains undocumented. We show that about 76% of insect species are inadequately represented in protected areas globally and that nearly 2% of species do not overlap with protected areas at all. The Post-2020 Global Biodiversity Framework that will likely drive PA growth provides a unique opportunity for nations to designate new areas that specifically consider insects' needs.

SUMMARY

Insects dominate the biosphere, yet insect populations are plummeting worldwide. Massive conservation efforts will be needed to reverse these declines. Protected areas (PAs) could act as a safeguard against extinction, but documented coverage of insect representation across the PA estate is limited. Here, we show that 76% of 89,151 insect species assessed globally do not meet minimum target levels of PA coverage. Nearly 1,900 species from 225 families do not overlap at all with PAs. Species with low PA coverage occur in North America, Eastern Europe, South and Southeast Asia, and Australasia. The Post-2020 Global Biodiversity Framework provides a guide to PA designations that require taking account of the needs of insects. Mapping important biodiversity areas must be upscaled to ensure nations capture insect diversity.

INTRODUCTION

Insects underpin the functioning of the biosphere, mediating pollination, herbivory, detritivory, plant architecture, and nutrient cycling among many other vital ecosystem processes.[1–5] They also influence the physiology and population dynamics of plants and provide a major food source for thousands of vertebrate species.[4–8] Insects pollinate some 80% of plant species, while at least 60% of bird species use insects as food.[7–9] Approximately 5.5 million species of insects occur worldwide, yet insect richness and abundance are collapsing,[5,7,10–16] with insect biomass down by 76% over 26 years in Germany[17] and insect abundance declining by 75%–98% over 35 years in Puerto Rico.[18]

Agriculture, climate change, urbanization, habitat loss, and habitat degradation are primarily driving insect declines.[7,14,19–24] Although species-specific conservation actions—such as captive rearing of Schaus' swallowtail *Papilio aristodemus*[25] and the wide-scale planting of host plants for Richmond birdwing *Ornithoptera richmondia*[26]—are important for preventing some extirpations, the sheer scale of insect diversity renders such intensive care too expensive and too slow to avert mass insect extinctions.[27]

Protected areas are generally effective in safeguarding habitats from loss and degradation[28–34]; therefore, ensuring adequate protected area (PA) coverage for insect species (especially those that are endangered) could help prevent insect extinctions worldwide.[32,35] PAs are defined by the International Union for Conservation of Nature (IUCN)[36] as "a clearly defined geographical space, that is recognized, dedicated, and managed through legal or other effective means, to achieve the long term conservation of nature." There have been numerous gap analyses on different taxonomic groups,[31,37,38] but the extent to which the distributions of insect species are represented by PAs remains poorly understood.[32,34,39] Some local studies have reported relatively high PA coverage of insects. For example, PAs contain 80% of freshwater insect species in Spain,[40] and butterfly species richness is greater in German PAs than in surrounding areas.[12] Yet, in contrast, other local studies find the opposite, with PAs in Bangladesh covering less than 2% of the geographic ranges of butterflies,[41] 83% of migratory butterflies inadequately represented by PAs globally,[42] PAs in Europe representing only 42% of the suitable habitat of the threatened beetle *Rosalia alpina*,[39] and 40% of insect species reported to be entirely absent from PAs in Costa Rica, the USA, and Mexico.[43] Given this substantial local variation, the extent to which insect species are covered by PAs globally remains obscure, meaning we are unable to track the progress of insect conservation globally.

Here, we measure insect representation in the global PA system using occurrence data from the Global Biodiversity Information Facility (GBIF).[44] We mapped the distribution of all extant insect species with at least three occurrence records in GBIF (n = 89,151) and compared their coverage by PAs with a target threshold[45–47] (see experimental procedures) set according to the geographic range size of each species. We developed species-specific range maps representing (1) the extent of occurrence (EOO; area within the shortest continuous boundary encompassing all known occurrence records) and (2) area of occupancy (AOO; the area within the EOO estimated to be occupied using alpha hulls), in both cases excluding records of known vagrant individuals.[48] We report AOO results in the main article and EOO results in Figure S3. We show that over 75% of insect species are inadequately represented in PAs globally. We call for an expansion of the global PA network that is insect smart, a key agenda item for the Convention of Biological Diversity's Post-2020 Global Biodiversity Framework.

RESULTS

PA coverage fell short of the target for 67,384 species (76%), indicating pervasive under-representation of insect distributions in the global PA system. The shortfall is much more severe than a similar global gap analysis conducted on vertebrate species, which found that 57% of 25,380 vertebrate species were inadequately covered.[37] PA coverage varied markedly among insect orders (Figure 1). Only three (Strepsiptera, Grylloblattodea, and Plecoptera) of the 28 orders had >25% PA coverage, with Strepsiptera having the highest coverage at 31.5%. There were three orders (Mantophasmatodea, Phthiraptera, and Thysanoptera) with <15% coverage, and the lowest was for Mantophasmatodea (12.12%; Tables S1 and S2; Figure S4).

The global distributions of 1,876 insect species (2%) do not overlap with PAs at all. These gap species were distributed across much of the world, with at least 100 gap species in the USA, Madagascar, Japan, Costa Rica, and Canada (see Figure S2). Gap species can occur because of sparse PA coverage, narrow species distributions, or a combination of both or simply under-recording of species distributions.[45] Our results are strongly influenced by narrow species distributions, with nearly 85% of gap species having a known AOO of <1,000 km^2. Of course, many insect species are extremely poorly surveyed, and geographic range size is likely to be vastly under-estimated for many, and perhaps most, of the species in our dataset. For example, more than 50% of beetle species in a sample from taxonomic revisions were known from one locality, and roughly 15% were known from a single specimen.[49]

Species with very small geographic ranges usually occurred either completely within PAs (very high coverage) or mostly outside them (no or very low coverage), while species with large geographic range size approximated the overall terrestrial PA coverage in their degree of representation inside the PA network (Figure S1). Mean coverage of AOO by PAs across all insect species was 19.24% (89,151 species). This is greater than the overall proportion of the terrestrial surface that is covered by PAs (15.73%), suggesting either biases of PAs toward insect distributions or biases in the available occurrence records of insects toward PAs.[46]

Relatively high proportions of insect species achieved target PA coverage in Amazonia, Africa, Saharo-Arabia, Europe, Western Australia, the Neotropics, Afrotropics, and Eastern and Central Europe, but protection fell short of target levels for many species in North America, Eastern Europe, South and Southeast Asia, and Australasia (Figure 2). If this is caused by under-estimation of geographic range size in tropical regions, our results of PA overlap are likely to under-estimate true coverage.

We detected substantial variation in PA coverage among insect families (n = 827). Mean PA coverage across the species in the family was 100% for only one (Mengenillidae), <15% for 28% of families, and there was no coverage for seven families (Ametropodidae, Ateluridae, Cecidosidae, Mnesarchaeidae, Monomachidae, Palingeniidae, and Styloperlidae). There were 22 families for which 100% of species met the representation target, but the proportion of species meeting the representation target was very low for the remaining families (Tables S1 and S2). For about 27% of families (n = 227), no species achieved the representation target, and 525 families had at least 75% of their species missing the representation target (Figure 1). Of the highly diverse orders that comprise at least 10,000 species in GBIF (e.g., Lepidoptera, Coleoptera, Diptera, and Hymenoptera), Coleoptera had the greatest proportion of families meeting target levels of protection (29%; Figure 1).

DISCUSSION

In the last few decades, growth in the PA estate has increased markedly,[47] but this growth has not generated a major increase in coverage for species and ecosystems of concern.[28] Our research now confirms this pattern since we show that the current PA estate is inadequate for conserving >75% of insect species, even against relatively modest targets. A core component of the current draft Post-2020 Global Biodiversity Framework (GBF)[29] of the Convention on Biological Diversity is being set up to drive a new ambition for PA growth that could provide a unique opportunity for nations to guide new PA designations

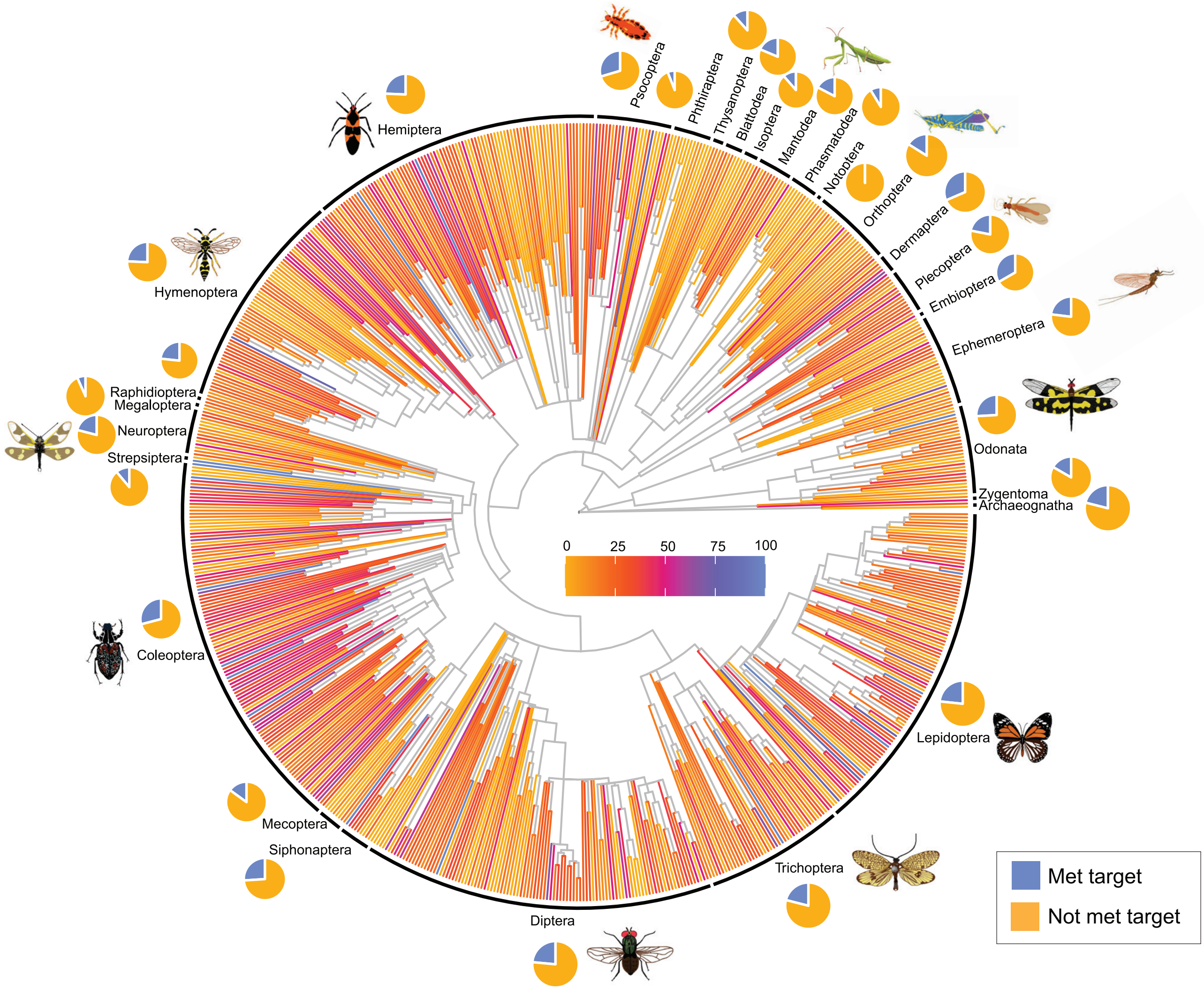

Figure 1. Taxonomic variation in PA coverage among insects using area of occupancy to depict geographic distribution
Phylogenetic information is derived from TimeTree[35] (see Figure S3 for the extent of occurrence results).

that specifically take account of the needs of insects. There is a new proposed target aimed at securing 30% of land and sea by 2030, which, if aimed at securing important biodiversity areas, could help overcome previous issues with PA bias[28,32,38,42] and help target important areas for insect conservation.

Scientists and planners must now step up and help with this challenge of identifying sites of importance for insect conservation, as a current major shortfall is how insects are captured in current biodiversity planning efforts.[6,14,28,29,32] Initiatives of major conservation organizations are inadequately capturing the needs of insects. For example, key biodiversity areas (KBAs) have been argued by many non-government organizations to be the "global standard" for identifying "important biodiversity areas" for site-based conservation,[48,50] yet only 0.02% (22 species) of targeted species to establish KBAs are insects (https://www.keybiodiversityareas.org/kba-data). Now is the opportunity for the scientific community to correct these biases by systematically resourcing and prioritizing insect mapping and target selection.[32,51]

Some insects are declining within PAs.[7,12,13,32] Threats such as rapid environmental change; habitat alteration, fragmentation, and loss; human settlement; agricultural expansion and intensification; and loss of corridors and roads inside PAs suggest that insects are facing an existential risk,[1,7,32,52,53] yet very little is known about their distribution and exposure to these threats. A new wave of surveys and monitoring is needed, perhaps fueled by the explosive growth of citizen science globally.[32,54–56] Active management of threatening processes occurring within the existing PAs is critical, for example by planting nectar and larval-feeding plants, especially those that are suitable for threatened species, or restoring freshwater resources inside PAs.[4,15,32] Insects utilize diverse vegetation structures and habitat requirements that vary markedly between and within families and orders.[2,4,6] Management for insects may mean increasing landscape heterogeneity, reducing pollution, minimizing insecticide or pesticide use, reducing importing ecological harmful products, and avoiding introducing invasive species.[2,6,14,32,57] Many insects bring joy to human visitors,

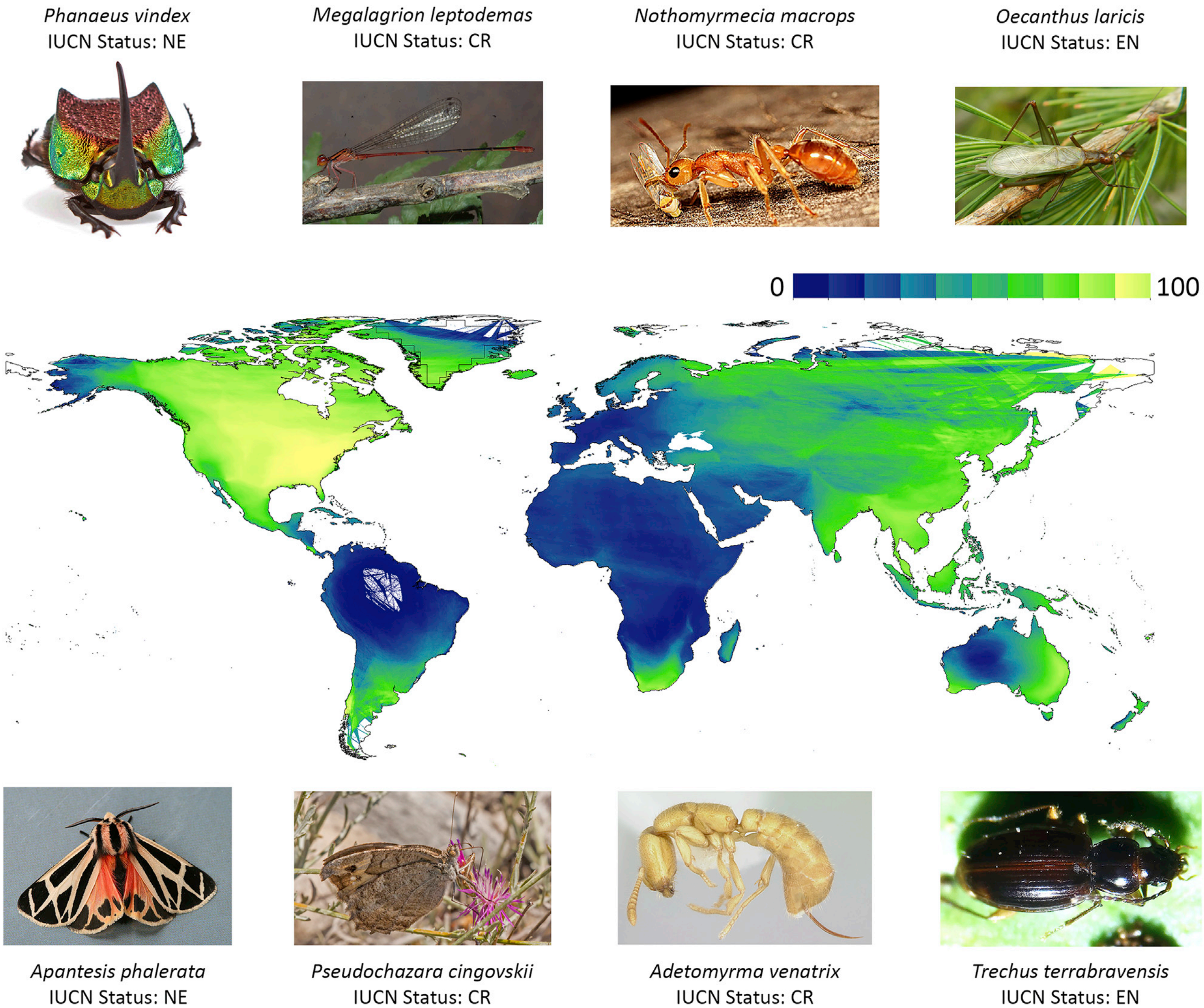

Figure 2. Insect representation in PAs showing the percentage of insect species not meeting the representation target (using the AOO) at 1 km^2 pixel resolution

Some example species for which the target representation was not achieved are given (CC-BY licenses). The source of these photographs are the following: California Academy of Sciences (*Adetomyrma venatrix*); Alejandro Santillana (*Phanaeus vindex*); Charles J. Sharp (*Pseudochazara cingovskii*); Seabrooke Leckie (*Apantesis phalerata*); US Fish & Wildlife Service – Pacific Region (*Megalagrion leptodemas*); Ajay Narendra (*Nothomyrmecia macrops*); Cuthrelld (iNaturalist user ID, *Oecanthus laricis*); and Kyli00 (Wikipedia user ID, *Trechus terrabravensis*). CR, Critically Endangered; EN, Endangered; NE, Not Evaluated. The color ramp represents the percentages of species not meeting the representation target, which increases from blue to yellow.

and insects are often the target of citizen science participation and capacity-building workshops, enhancing restoration and conservation programs.[2,44,55] Since most insects are herbivorous or are tied to plants, it has been suggested that the global biodiversity hotspots with more than 50% of endemic plant species could harbor a high proportion of terrestrial insect species and provide some protection if more PAs are placed within them.[49]

This first global attempt to assess the performance of existing PAs in conserving insects reveals stark shortfalls, but our findings must be interpreted cautiously. First, of the estimated 5.5 million insect species globally,[5] we could only model the distributions of 89,151 species. The unmodeled species might have much lower or higher PA coverage than those we were able to include here. Further research is needed to determine if estimated protection level varies systematically across species with dense versus sparse occurrence data after accounting for geographic range size. Second, it is possible that our results are affected by spatial variation in the extent to which occurrence records are themselves biased toward PAs. Habitats within some PAs might be unsuitable for particular insects even though the area is within the overall distribution of the species, and our maps of insect distributions will be overestimated for some species and under-estimated for others. Future studies can fine-tune estimates of the effectiveness of PAs for insect conservation by assessing habitat suitability within PAs and determine priorities for expansion of the global PA estate to efficiently increase insect protection.

Despite being enormously diverse and driving many ecosystem processes and functions, insects have been largely neglected in global conservation assessments.[2,6,32,58] A suite of influential studies has reported dramatic insect declines in many parts of the world, mostly due to anthropogenic stressors.[7,14] Although PAs are actively insulating many vertebrate species from key anthropogenic threats, the extent to which this is true for insects remains largely unknown. Here, using distribution records from the largest biodiversity data repository, we conducted the first-ever global gap analysis for insects. We showed that three-quarters of insect species were inadequately represented in PAs and that >2% species had no coverage at all. We hope our results will stimulate efforts to improve knowledge on the distributions of insects, manage existing PAs more effectively for insects, and identify key areas for future PA expansion.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Shawan Chowdhury (s.chowdhury@uqconnect.edu.au).

Materials availability

This study did not generate new unique materials.

Data and code availability

We downloaded all the data from public repositories. The DOIs of the geospatial data are https://doi.org/10.15468/dl.tavumq, https://doi.org/10.15468/dl.szp1si, https://doi.org/10.15468/dl.yzulee, https://doi.org/10.15468/dl.ihepwh, and https://doi.org/10.15468/dl.szyiv7.

The code used to reproduce the analysis can be accessed at https://github.com/ShawanChowdhury/InsectConservationPA.

Geospatial data

We downloaded occurrence records for all insects identified to species level in the GBIF (106,911,975 records).[59] Using the CoordinateCleaner[60] R package, we removed records with no longitude, latitude, or species name, spatial duplicates, records in the ocean, any imprecise coordinates (e.g., zero coordinates, locations assigned to biodiversity institutions, or around GBIF headquarters), and invalid coordinates where a country was specified that was incompatible with the coordinates given. We also removed fossil species with reference to the Fossilworks database (http://fossilworks.org), extinct species (https://www.iucnredlist.org), and species with less than three unique locality records, as a polygon depicting a range map cannot be drawn where there are fewer than three unique localities.

Range maps

We calculated a geographic range map for each insect species using two alternative methods for depicting their geographic distribution—EOO and AOO. We estimated EOO by constructing a minimum convex hull encompassing all occurrence records for a species using the rgeos[61] package. This EOO polygon spans the full known distribution of each species and makes no assumptions about the pattern of occurrence within that overall distribution.[62] The EOO will only under-represent the true distribution of a species in cases where the species occurs in localities beyond the EOO but where there are no corresponding records in GBIF. Within the EOO, it is likely that many areas are not actually occupied by the species, for example as a result of habitat discontinuities.[63] This could result in a PA overlap analysis incorrectly estimating the extent to which a species is actually represented in the PA system. To estimate the occupied area for each species, we created an alpha hull with an alpha value[64] of 2 using the rangeBuilder package.[65] The alpha hull method removes links between pairs of occurrence points that are more than twice (when alpha = 2) the mean nearest-neighbor distance apart and can split the EOO polygon into multiple smaller polygons depending on the distribution of nearest-neighbor distances. In all cases, the range map based on estimating the AOO in this way is either identical to the EOO or a spatial subset of it.

PA data

We downloaded the most recent PA map from the World Database on PAs[34] and prepared it for analysis.[28,41,66,67] First, we reprojected the map to an equal-area coordinate system (World Behrmann; ESRI: 54017). Second, we removed UNESCO biosphere reserves and sites with unknown or proposed status. Third, we extracted PAs represented only by a point locality, reprojected those to an equidistant coordinate system (World Equidistant Cylindrical; ESRI: 54002), buffered them using their reported area, and then merged them back into the original dataset.

PA overlap and representation target

We rasterized all spatial data at a unified 1 km^2 resolution using the fasterize[68] package and calculated the overlap between each species' two geographic range polygons and PAs using the raster[69] package. For each insect species, we established a target proportion of its global geographic range to be represented inside PAs using the same approach for both EOO and AOO. We followed previous studies that set the target at 100% for species with a distribution of $\leq$1,000 km^2 and the current global terrestrial PA coverage (15%) for those with $\geq$250,000 km^2 and interpolated on a log-linear scale between these thresholds[28,38,45–47] using the prioritizr[70] R package.

Phylogenetic tree

We retrieved the phylogenetic hypothesis displayed in Figure 1 from the TimeTree database[71] with "group" specified as "insecta" and "rank" specified as "family." We imported the data using the ape[72] R package and pruned it to represent only insect families represented in our biodiversity dataset. Finally, we created the tree using the ggtree[73] R package.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.12.003.

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AUTHOR CONTRIBUTIONS

S.C. conceptualized the idea, did the analysis, and wrote the paper. S.C., M.P.Z., and R.A.F. developed the experimental procedures. All authors contributed the experimental procedures, analysis, and writing of the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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