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Addressing Gaps in Butterfly Population Monitoring to Catalyze Global Insect Conservation

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ABSTRACT

The conservation community sorely lacks a global indicator of change in insect populations. Given widespread insect declines, addressing this gap is key for conservation and policy targets. We suggest that butterfly monitoring programs can serve as the foundation for an effective global network of insect monitoring. To assess this potential, we bring together an international consortium and calculate a "Global Butterfly Index" using the Living Planet Index approach. Based on 10,386 population trends of 213 univoltine species, we found that overall declines in butterfly populations are predictable based on species traits. Our effort should pave the way for the development of a global network of butterfly population monitoring schemes. Since butterflies are the best monitored insects and have strong emotional value for the public, a global infrastructure for butterfly monitoring can be a flagship for insect conservation, informing policymaking and spurring societal transitions towards sustainable futures.

1 | Introduction

Tracking the abundance of species' population size is a priority in biodiversity conservation (Geldmann et al. 2023). Population abundance is recognized as an Essential Biodiversity Variable that reflects key ecological factors including reproductive success, carrying capacity, susceptibility to extinction, and species' contributions to ecosystem functioning (Kissling et al. 2018). The importance of population abundance is also enshrined in Goal A of the Kunming–Montreal Global Biodiversity Framework (GBF). Therefore, high-quality and extensive time series of population abundance data are crucial to assessing progress towards global biodiversity goals and to inform the scale of action required to deliver them. Such data remain nevertheless uncommon, and when present, they often show strong taxonomic and geographic biases (Moussy et al. 2022). In fact, monitoring programs that adequately collate high-quality abundance time series data are lacking for most countries that are signatories to the GBF (Gonzalez et al. 2023).

While awareness of information gaps in population data is longstanding, efforts to address these gaps have primarily focused on vertebrates (Moussy et al. 2022). Thousands of time series describing the population abundances of bird, amphibian, reptile, fish, and mammal species have been collated to calculate the "Living Planet Index" (LPI) (Ledger et al. 2023). The LPI is an indicator that synthesizes data collected across multiple species to present a composite metric of how populations are changing over time. The LPI has played a critical role in global conservation (Ledger et al. 2023) and in steering public opinion since the 1990s, because it more succinctly represents biodiversity change than thousands of constituent population trends, and due to its endorsement by major environmental organizations and governments (Ledger et al. 2023). In stark contrast, owing to a lack of data on population trends, insects and other invertebrates have often been neglected in the global conservation agenda (Chowdhury et al. 2023).

The continued underrepresentation of insects in conservation is of significant concern. Insects not only account for ∼70% of terrestrial aboveground species and half of the animal biomass on earth (Díaz and Malhi 2022), but are also critical components of the food web and are instrumental to fundamental ecosystem processes, including pollination, herbivory, predation, and decomposition (Wagner et al. 2021; Blüthgen et al. 2023). Since populations of different lineages do not necessarily follow similar trends (Outhwaite et al. 2020), with taxa often responding to environmental and anthropogenic pressures idiosyncratically, inferring how insect populations are changing based on trends in vertebrates is challenging and might even be misleading. Sustaining nature and its contributions to people will therefore require understanding of the causes of insect declines, and the identification of solutions that can mitigate the risk of catastrophic collapses in these taxa (Wagner et al. 2021; Blüthgen et al. 2023).

A series of recent studies have already reported insect declines, although restricted to a relatively narrow group of insects and from a few regions of the globe (e.g., van Klink et al. 2023, Edwards et al. 2025). Such studies have spurred widespread concern, working as a "canary in the coal mine" for the global status of insects and biodiversity in general (Wagner et al. 2021; Blüthgen et al. 2023). Yet, the taxonomic and ecological diversity of these taxa generates several challenges for assessing population trends. For instance, many insect groups are difficult to identify, are highly diverse, and exhibit considerable fluctuation in abundance across multiple temporal scales, posing challenges for accurate monitoring (Didham et al. 2020; Forister et al. 2023). Therefore, abundance trends in insects remain poorly understood globally.

Systematic and long-term insect monitoring programs are crucial for the high-quality data needed to address these challenges. Critically, standardized monitoring in fixed locations allows comparable abundance data for robust trend assessments and thereby differs fundamentally from opportunistic records of the occurrence or abundance of species. However, outside a few wealthy economies, standardized monitoring remains uncommon because such programs are typically resource-intensive and rely on considerable expertise on the local entomofauna. We suggest that the lack of knowledge around population abundance trends in insects, particularly in terrestrial insects, is a conservation paradox given their fundamental roles in ecosystems. Heightened recognition of insect declines amongst researchers, policymakers, and the wider public offers a timely imperative to address this disparity during the implementation of the new GBF.

Here, we argue that butterflies should be a priority taxon on which to ground the development of a global infrastructure for monitoring insect populations. Beyond having a long tradition of monitoring (Warren et al. 2021), butterflies are cross-culturally appreciated as being among some of the most charismatic animals (Thomas 2016). These taxa thus have the potential

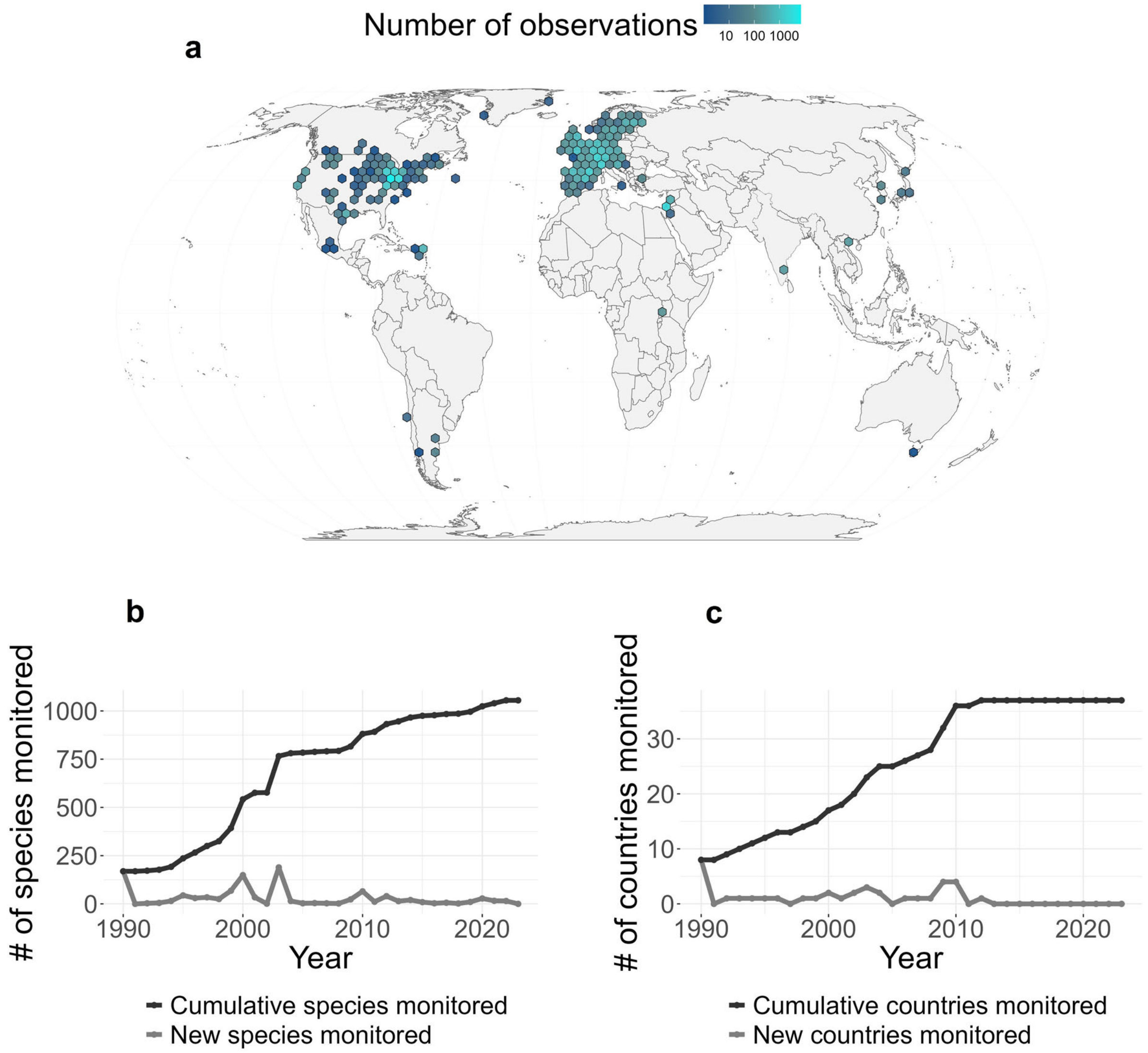

FIGURE 1 | Map illustrating sampling effort (a) number (#) of observations within a ∼ 200-km hexagonal grid) and trends in species monitored and countries covered (cumulative number of species, (b) and number (#) of countries, (c), represented in the dataset) in the global butterfly population from standardized monitoring efforts. In (b, c), grey lines represent the species and countries added to global butterfly monitoring efforts. Increases have been slow and steady since 2010, but have halted since then.

to enhance public engagement and scientific communication regarding insects, as well as the likelihood of political interest for conservation. Butterflies also play key ecological and economic roles (e.g., herbivory and pollination Slade and Ong 2023), and while unlikely to be representative of all insect taxa, have been widely used as ecological indicators of responses to environmental change (Warren et al. 2021). Thanks to ever-expanding monitoring programs, we have strong evidence highlighting the decline of butterfly populations in many regions around the globe (Thomas 2016; Warren et al. 2021; Edwards et al. 2025). Therefore, expanding ongoing efforts for monitoring butterfly populations globally will be important for butterfly conservation and, more broadly, to advance the protection of insects, providing the shortest path to creating a first global indicator of insect populations.

We begin by examining how butterfly monitoring efforts have evolved in the last three decades in terms of spatial and taxonomic coverage (Figures 1 and 2). We then analyze population trends using the LPI approach (Figure 3; see supplementary materials S1 for details on the methods). Building on this assessment, we delineate the next steps necessary for developing an efficient, representative, and global monitoring network for butterfly populations. Operationalizing such a network will be fundamental for developing the first truly global indicator of insect population abundance trends.

2 | Global Patterns in Butterfly Monitoring

We collated 45,492 population time series from 1055 butterfly species, sampled between 1990 and 2023 in 3636 locations from 37 countries (Figures 1–3). This is the most extensive dataset to date that represents populations of a single insect group and one of the largest datasets collated for population abundance trends. For comparison, the 2018 LPI includes 31,821 population time series

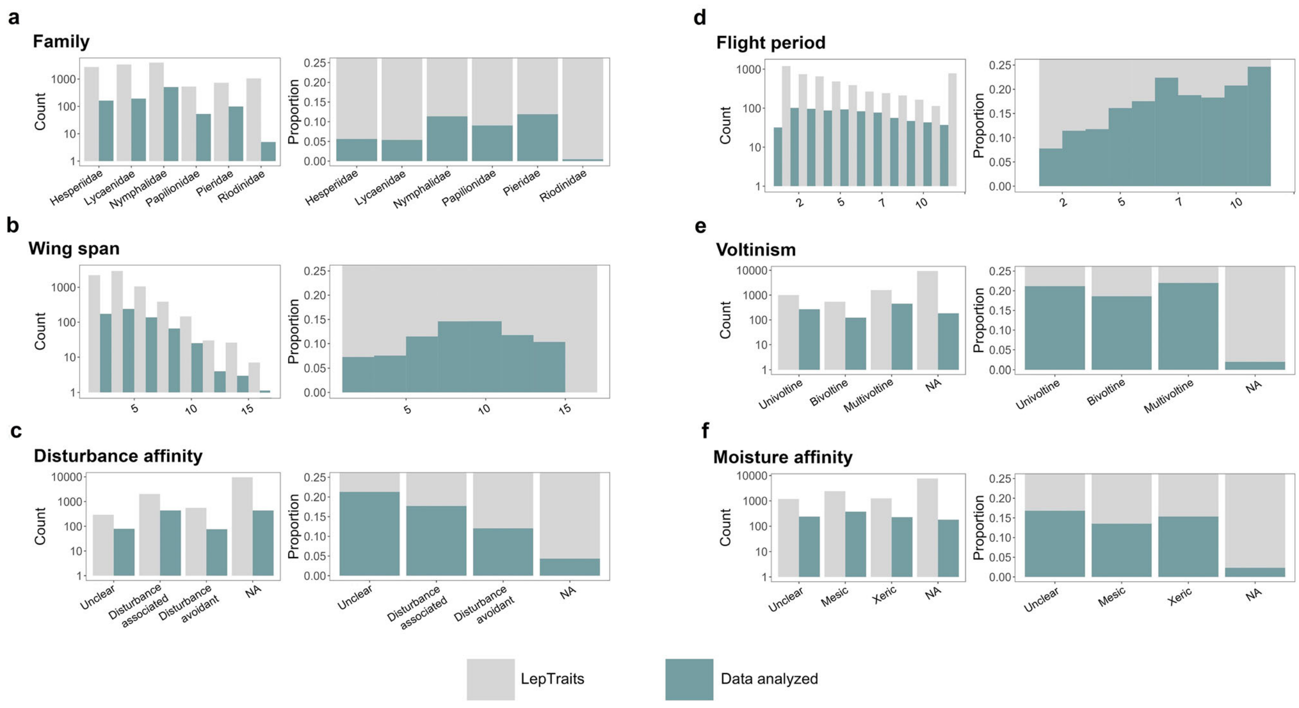

FIGURE 2 | Representativeness of species sampled by global butterfly population monitoring efforts in relation to six traits. For each trait, we show the total number of observed species in our sample (green color) versus the total number of species documented in LepTraits (Shirey et al. 2022), with the left inset showing the total number of species in different categories ("Count"), and the right inset showing the ratio of species in relation to the entire species list in LepTraits ("Proportion"). Note that, for each of six traits assessed (family, [a]; wing span, [b]; disturbance affinity, [c]; flight period, [d]; voltinism, [e]; and moisture affinity, [f]) the right plot is capped at 0.25 on the *y*-axis because all bars go to 1.00.

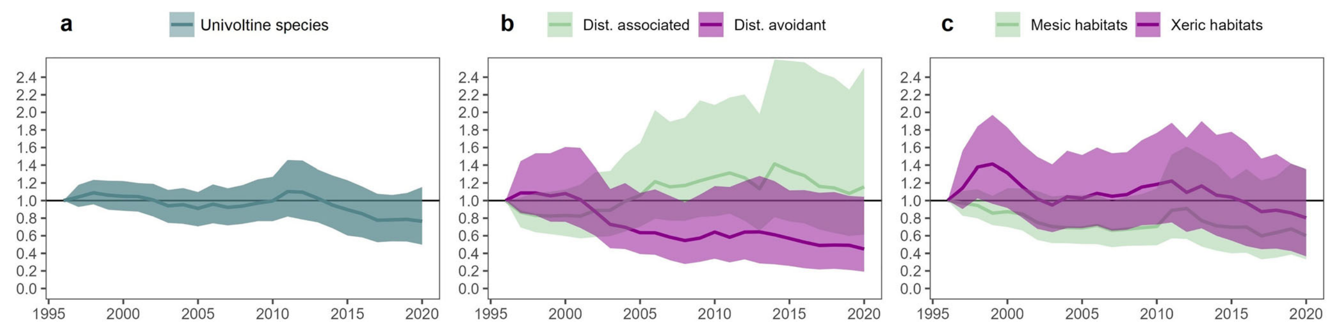

FIGURE 3 | Analyses with the Living Planet Index (LPI) algorithm of univoltine species in our sample. Overall, the LPI indicators declined when considering all species in our sample (left inset, a), and increasingly so when considering candidate sensitive species, that is, species that avoid disturbed habitat (central inset, b) and species adapted to mesic (medium moisture) and xeric (dry) habitats (right inset, c).

for 5230 vertebrate species (Ledger et al. 2023). While spatial gaps in our dataset are extensive (Figure 1), the number of species and countries monitored has increased steadily in the past 35 years, demonstrating progress within the indicator timeframe (Figure 1, bottom row). Still, the rate at which new species and countries have been added to butterfly monitoring efforts has decreased after 2010. We hope that the GBF will be an opportunity to regain momentum. In addition to spatial biases in data availability (Figure 1), the 1055 species monitored represent only 5.2% of the global butterfly fauna (Pinkert et al. 2022) and do not constitute a representative random sample (Figure 2). Past monitoring efforts over-represent species with longer flight periods, belonging to the Nymphalidae and Pieridae families, of intermediate body sizes, and associated with sites disturbed by human activities (Shirey et al. 2022) (Figure 2). Notably, for many species globally, data on these traits are still missing and/or their natural history remains unclear (Figure 2).

3 | Insights and Challenges From the First Global Butterfly Index

Next, we calculated a "Global Butterfly Index" following the LPI approach (McRae et al. 2025). Because this approach is based on abundance growth rates calculated yearly, and bivoltine or multivoltine species are likely to increase their number of generations with increasing temperatures, we restricted our analysis to 10,386 populations belonging to 213 univoltine species sampled between 1995 and 2020. Consistent with a large-scale analysis in the USA (Edwards et al. 2025), the indicator showed an average decrease in butterfly populations (indicator value = 0.76, 95% CI = 0.49–1.15), although such change is not statistically significant. Re-analysis of geographical subsets of the data shows that uncertainty in the indicator originates predominantly from areas under sampled and variability in the magnitude of trends between regions. However, areas with higher sampling coverage showed significant declines, in North America (indicator value = 0.37, 95% CI = 0.19–0.73), and non-significant declines, in Europe (indicator value = 0.79, 95% CI = 0.62–1.05), whereas the rest of the world, with much poorer coverage, shows growing but highly uncertain trends (indicator value = 1.43, 95% CI = 0.32–4.9).

To gain a better insight into these declines, we also re-analyzed subsets of the data based on two candidate predictors of negative responses to global change—avoidance of disturbed habitats, and dependence on mesic or xeric habitats (Forister et al. 2023; Riva et al. 2023). As expected, we found that 32 species (1262 populations) that avoid disturbance in our sample have declined more steeply on average (indicator value = 0.44, 95% CI = 0.19–1.04), whereas 49 species (4010 populations) associated with disturbed habitats have increased on average (indicator value = 1.15, 95% CI = 0.61–2.51), although with considerable uncertainty. Similarly, 85 species (3550 populations) associated with mesic habitats and 59 species (3373 populations) associated with xeric habitats displayed steeper declines on average (indicator value = 0.59, 95% CI = 0.33–1.35 and indicator value = 0.80, 95% CI = 0.36–1.34 respectively), suggesting that species with narrower habitat niches are disproportionately suffering in our dataset from across the globe. Although uncertain (confidence intervals that overlap one, i.e., no change), these results align with widespread expectations that some butterfly populations are most likely to decline in the face of global change, and that traits can aid in predicting these sensitive populations.

4 | Priorities for a Global Network of Butterfly Population Monitoring Programs

Our results support the value and great potential of butterfly-based indicators, but also underscore the need for a better understanding of butterfly population trends, with widespread declines emphasizing the urgency of this need (Figure 3). Furthermore, they illustrate that generating a global indicator of butterfly populations will require both expanding the geographic coverage of sampling (Figure 1) and counterbalancing current biases in species representativeness (Figure 2).

A step-change in monitoring has been called for by the scientific community due to evident spatial biases (Kühl et al. 2020; Gonzalez et al. 2023). Most of our observations originate from Europe and North America (Figure 1), which severely limits the ability to infer trends in butterfly population abundance globally, and particularly for most countries supporting the GBF (Figure 1). While expanding monitoring efforts to underrepresented regions will be important to develop a robust global indicator of butterfly populations, our study also points to the clear necessity to implement monitoring protocols towards targeting the less common or less detectable species in programs that are currently ongoing (Figure 2). Finally, coordination and adoption of best practices in data quality, access, and sharing will be central for a global monitoring program to emerge from scattered initiatives (Kissling et al. 2018; Kühl et al. 2020). Robust inferences from multiple data sources can be facilitated by modern analytical approaches; however, such approaches will be most powerful when the envisioned monitoring network follows fundamental data standards (Kühl et al. 2020).

How can we rapidly enhance geographic coverage of monitoring efforts while consolidating robust data standards? The past teaches us that coordinated efforts, together with dedicated policies, can accelerate progress. Existing butterfly monitoring programs demonstrate that it is possible to develop, maintain, and expand these efforts in concert. In particular, the growth of the European Butterfly Monitoring Scheme (https://butterfly-monitoring.net/) and the North American Butterfly Monitoring Network (https://www.thebutterflynetwork.org/) demonstrates how coordination and investment can result in the successful adoption of common standards and practices. Butterfly monitoring programs are also in development or have been launched in tropical, traditionally data-deficient countries such as India (Indian Butterfly Monitoring Scheme [iBMS], https://www.ibms-network.in). Transferability of tools and experience will facilitate such coordination, although the human capital—particularly harnessing the enthusiasm and knowledge of coordinators and communities of knowledge—and economic capital are often the key limiting factors in the establishment of new programs. From the European experience, sharing and co-developing capacity with a dedicated network has been crucial to scaling up butterfly monitoring across the continent and overcoming many of the logistical and technical hurdles that can be daunting for new monitoring schemes.

Complementing and expanding previous efforts will ensure value for money and maximize returns from previous investments. Although our study does not include all ongoing butterfly monitoring programs, our results show that the recent expansion of butterfly monitoring worldwide has already resulted in a notable increase in data coverage, contributing to our understanding of global trends in insect populations (Figure 1). Future efforts should target the development of new monitoring programs in regions where long-term data on butterfly populations are still absent, expand ongoing initiatives to better capture underrepresented species, and strive to increase the availability of datasets and cooperation between data providers that did not participate in our study. We are confident that these advancements will help develop increasingly informative global butterfly indices in the coming decades. Nevertheless, this will require both political and financial support. We therefore call for participation and support in the development of a global network of butterfly population monitoring programs.

While insects have only recently been included in conservation regulations, such inclusion has certainly promoted formal monitoring programs. For instance, the North American Breeding Bird Survey has informed biodiversity conservation and management in the United States and Canada since the 1960s. While the European Grassland Butterfly Indicator was first proposed in

2005. Despite its shorter history, the European Grassland Butterfly Indicator is now used by the European Environment Agency and was included in the recent Regulation on Nature Restoration adopted by the European Union in 2024. Moreover, member states of the European Union are also required to "*reverse the decline of pollinator populations by 2030 and achieve thereafter an increasing trend*." Similar goals are set in the GBF, but without a system to monitor insect populations nationally and globally, it will be impossible to assess the effectiveness of management actions implemented to achieve these targets.

5 | Outstanding Challenges

Progress requires resolving some outstanding challenges, not least of which is the many practicalities of establishing a global network of monitoring programs. For instance, spatial gaps in monitoring efforts compound the fact that traditional monitoring approaches are not fit for hyper-diverse insect communities (Slade and Ong 2023). While monitoring schemes in Europe and North America rely largely on volunteer contributions, this model is not suitable in all regions of the world. Generating high-quality population time series will be more challenging in many low- and middle-income countries, particularly in the tropics, where species identification is more challenging. While citizen science is growing steadily and provides both tools and insights for conservation, in some areas, it might be difficult to safely conduct biological monitoring through citizen science activities. Furthermore, most biodiversity data, particularly from citizen science activities, will not be easily obtained from the most remote and pristine areas globally, thus perpetuating traditional biases in our understanding of biodiversity (Hortal et al. 2015). Professional surveys might partly address this issue and improve the coverage in many parts of the world, yet incomplete checklists (Pinkert et al. 2022) and/or a lack of experts (Löbl et al. 2023) might limit the advancement of monitoring in some regions. Furthermore, when monitoring populations is feasible, the selection of monitoring sites and sampling approaches are crucial decisions that often involve trade-offs (Forister et al. 2023). Past experiences highlight that in some regions and environments, monitoring programs should adopt complementary protocols, such as a combination of bait trapping and more widely used transects or point counts to sample both butterfly species inhabiting the canopy and the forest understory. Nevertheless, it remains unclear which approach will be most effective in which environment; this requires testing of the applicability of different sampling methods.

Previous studies have also highlighted analytical challenges that emerge after data collection. Analyses of population abundance data are sensitive to the shifting baseline syndrome (Papworth et al. 2009) and other modeling assumptions. Furthermore, indicators by design synthesize complex multivariate information, making their calculation and interpretation challenging. For instance, the LPI approach used here responds to modeling choices including the length of time series, potential weights across regions, and many other analytical decisions (McRae et al. 2025). Such decisions must be carefully considered when integrating insect taxa in frameworks established within a global conservation agenda that has long focused on other taxa. For example, because many butterfly species are multivoltine, it is unclear how an increase (or decrease) in the number of generations and the total abundance reported within each generation can be discriminated with the LPI, which is based on yearly abundance estimates. Here, we focused on univoltine species to overcome this issue, but this clearly reduces the scope of the indicator. We emphasize that our index is a prototype indicator of global butterfly populations: in addition to caveats about data biases, research is required to determine what modifications to the LPI method (e.g., smoothing) would be needed to make it robust to the kind of large interannual fluctuations exhibited by many butterfly populations. It remains unclear how insects will translate to widely-adopted indicators given their natural histories (Ledger et al. 2023), and it is revealing that the goals and targets of the GBF could deliver benefits for insect conservation, but indicators currently proposed to measure progress are likely to be insensitive to changes in the status of these taxa.

6 | Towards a Global Indicator of Insect Population Abundance Trends

We hope that our assessment will serve as a rallying call to drive new efforts in butterfly population monitoring and that such efforts will ultimately facilitate the development of an extensive global monitoring network for insect populations. While this will be a long and winding road, we are hopeful that the challenges we outlined above can be solved. We also believe that further capitalizing on past investments is the path of least resistance that is most likely to catalyze progress towards an operational global indicator of terrestrial insect populations. Therefore, building on existing monitoring programs designed for tracking butterfly populations should be a priority in the GBF. Specifically, leveraging established schemes could involve hosting training workshops, creating exchange programs for early-career researchers, expanding programs through shared infrastructure (for monitoring—https://butterfly-monitoring.net/bms-schemes; for biodiversity atlases—https://www.bioatlasindia.org; for communities-building—https://www.inaturalist.org), and developing funding mechanisms that prioritize cross-regional partnerships (e.g., through the IUCN Species Specialist Group—Butterfly and Moth Specialist Group) and capacity building (Chowdhury et al. 2025).

Although focusing on butterflies has its limitations, it represents a tangible and achievable step towards generating global information on insect declines—and arguably, something that cannot be derived from the current vertebrate-focused global biodiversity indicators. In this context, understanding how well trends in butterfly populations relate to trends in the abundance of other insect and invertebrate taxa will be key for a GBF that embraces "the little things that run the world."

In conclusion, the past decades have shown important developments in the monitoring of butterfly populations. To turn our draft metric into an authoritative index would require a concerted program of work to properly account for the uneven sampling across the globe (perhaps using geographic weighting) and to identify what modifications to the LPI approach might be desirable. But any analytical developments hinge on more representative coverage of monitoring schemes. We argue that it is opportune for the scientific community to capitalize on this momentum and increase focus on biodiversity monitoring through global, national, and regional target-setting. Better access to data collected in the past, combined with growing monitoring efforts in underrepresented regions, has the potential to produce urgently needed indicators of insect population trends. Efforts to bring insects into global policy frameworks will require substantial resources, but are essential. Lacking national butterfly monitoring schemes, as perhaps the most iconic insect group for monitoring efforts, precludes the inclusion of insects into national biodiversity targets and national reporting towards the GBF. Butterflies could also play a vital role in guiding societal transitions toward environmental sustainability, facilitating societal dialogues and policy development. Sustaining and expanding monitoring programs targeting butterfly populations could therefore be critical for the GBF to truly capture variation in biodiversity change across the tree of life as we progress in the Anthropocene.

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Data Availability Statement

The data that support the findings of this study are available from the authors.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Material: conl70037-sup-0001-SuppMat.docx