Strategic conservation of tropical insects

Shawan Chowdhury*[1a,b], Syeda F Jahan[2], Perpetra Akite[3], Yanina Benedetti[4], Timothy C Bonebrake[5], André VL Freitas[6a,b], Md M Hossain[7], Richard J Ladle[8], Federico Morelli[4,9], Nigel Stork[10], Krushnamegh Kunte[11]

* corresponding author

[1]dr.shawanchowdhury@gmail.com; https://orcid.org/0000-0003-2936-5786
[1a]School of Biological Sciences, Monash University, Melbourne, VIC, Australia
[1b]Biodiversity Society, 49/1 Babar Road, Dhaka 1207, Bangladesh

[2]Department of Zoology, University of Dhaka, Dhaka, Bangladesh; sfjahan5@gmail.com;

[3]College of Natural Sciences, Makerere University, Kampala, Uganda; perpetra.akite@gmail.com; https://orcid.org/0000-0002-0302-1822

[4]Czech University of Life Sciences Prague, Faculty of Environmental Sciences, Kamýcká 129, CZ-165 00 Prague 6, Czech Republic; ybenedetti73@gmail.com; https://orcid.org/0000-0003-1600-2310

[5]School of Biological Sciences, The University of Hong Kong, Pokfulam, Hong Kong SAR, CN; tbone@hku.hk; https://orcid.org/0000-0001-9999-2254

[6a]Laboratório de Ecologia e Sistemática de Borboletas, Departamento de Biologia Animal, Instituto de Biologia, Universidade Estadual de Campinas, Campinas, São Paulo, Brazil; baku@unicamp.br; https://orcid.org/0000-0002-5763-4990

[6b]Museu de Diversidade Biológica, Instituto de Biologia, Universidade Estadual de Campinas, Campinas, São Paulo, Brazil
[7]Department of Zoology, Jahangirnagar University, Dhaka 1342, Bangladesh; monwar@juniv.edu; https://orcid.org/0000-0002-4380-7280

[8]Institute of Biological and Health Sciences, Federal University of Alagoas, Maceió, Brazil; richardjamesladle@gmail.com; https://orcid.org/0000-0003-3200-3946

fmorellius@gmail.comhttps://orcid.org/0000-0003-1099-1357[9]Institute of Biological Sciences, University of Zielona Góra, Zielona Góra, Poland; fmorellius@gmail.com; https://orcid.org/0000-0003-1099-1357

[10]School of Environment and Science, Griffith University, Nathan, Queensland, Australia; nigel.stork@griffith.edu.au; https://orcid.org/0000-0001-7812-2452

[11]National Centre for Biological Sciences (NCBS), Tata Institute of Fundamental Research (TIFR), GKVK Campus, Bellary Road, Bengaluru 560065, India; krushnamegh@ncbs.res.in; https://orcid.org/0000-0002-3860-6118

Keywords

Biodiversity monitoring, conservation policy, citizen science, pollinators, Lepidoptera

Highlights

1. Insects play a central role in many ecosystem functions, yet they are largely neglected in conservation assessments, and many species are declining.

2. At least 80% of insect species live in the tropics; however, our understanding of tropical insect species and their distribution is vastly limited, as most species are yet to be discovered.

3. We identify four primary factors contributing to the tropical insect data gaps and provide strategies to mitigate them.

4. Using Bangladesh as a case study, we provide evidence on how this framework can be applied to other tropical countries.

5. While our framework is developed for insects, it can be broadly applied to any other poorly known taxa.

Outstanding questions

1. How can we establish sustainable, long-term insect sampling and monitoring programmes in tropical regions?

2. In what ways can citizen science platforms be modified and advertised to enhance participation in the tropics?

3. How do conservation efforts vary between widely distributed and narrow-range endemic insect species, and how can spatial prioritisation tools be improved to account for these differences?

4. Can automated technologies, such as AI-based image recognition, acoustic sensors, and radar, be effectively scaled for monitoring tropical insect biodiversity, and what limitations do they have?

5. What are the most effective indicators for assessing the success of insect conservation efforts in the tropics, and how can these indicators be monitored across large geographic areas and diverse taxonomic groups?

Abstract

Insect species are declining globally, yet they are often overlooked in biodiversity conservation measures. The tropics harbour > 80% of all insect species; however, information on their ecology and conservation status is largely lacking. It is imperative to identify solutions to the issues of data availability and integration of scientific findings with conservation policy for tropical insects. To achieve this, we assembled a global team of experts and identified four major challenges: global visibility, data shortfalls, lack of infrastructure, and insufficient conservation action. We developed a framework for potential solutions to conserve tropical insects and tested it in Bangladesh, a densely populated tropical country. Our framework applies broadly to governmental obligations for biodiversity conservation in tropical countries worldwide.

The status of insects

Insects are the Earth's most diverse animal group by far, representing 50% of named species, with more than 80% predicted to be still undocumented [1], not including the very high number of morphologically cryptic species [2]. They play critical roles in ecosystem processes and functioning and enhance the world's food production [3]. Insects pollinate over 80% of wild plant species and 75% of flowering plant species, while 60% of bird species rely on insects as an indispensable food source [4]. They also play crucial roles in nutrient cycling, food webs, herbivory, frugivory, and population control through parasitoidism [4, 5].

Anthropogenic impacts on Earth are accelerating, with 60% of terrestrial areas under moderate or intense human pressure [6]. Natural intact vegetation has been reduced to less than 10% in most global biodiversity hotspots [7]. These factors bear consequences for the highly endemic fauna and flora of these hotspots. The ever-growing human population is causing many species to disperse, decline, and in some cases go extinct [8, 9]. Like other animal groups, many insect species are declining, primarily due to habitat loss, climate change, and pollution [10, 11, 12, 13]. For example, insect populations are estimated to have declined by 45% globally over the last four decades [10], with flying insect biomass dropping by 76% in protected areas and natural reserves in Germany [14]. Furthermore, global terrestrial insects are predicted to be declining at 1% annually [15], and butterfly abundance decreased by 22% between 2000 and 2020 in the United States [16]. While most of these studies have focused on well-known temperate faunas, the evidence for declines in tropical forests is growing [17]. Further, increasing intensity of ENSO events due to climate change has been linked to declines in the tropics of insect diversity and reduced insect-mediated ecosystem functions (decomposition and leaf herbivory) [18]. Researchers have also highlighted inherent biases in the sampling methods of several insect decline studies [19]. Therefore, integrating multiple layers of evidence is necessary to properly understand the decline in insect diversity and populations [20]. Additionally, there is strong evidence that insects receive significantly less focus and research funding than other groups, especially vertebrates such as birds and mammals [21], which creates a bias in conservation research, policy, and funding [22].

Insect decline could be global and widespread, yet most long-term studies on insects are from temperate regions, which represent only 20% of the global insect diversity [1, 17]. Similar to many other taxa, insect species are unevenly distributed, with the tropics harbouring the vast majority of the described and undescribed species and biodiversity hotspots [23, 24, 25]. Tropical forests cover less than 5% of the Earth's land surface but contain over half of the described species and 80% of insect species [1]. Nevertheless, many tropical insects are declining, too, primarily due to habitat loss, agricultural intensification, and climate change [17, 18, 26]. For example, between 1976 and 2012, climate change was associated with a decline in insect biomass 4-8-fold in sweep samples, 30-60-fold in sticky trap catches, and 35-fold in group-trap catches [27, but see 28], and conservation areas cannot always minimise such threats [29]. New analyses of bark and rove beetles [Scolytinae and Staphylinidae] further suggest that most insect species have yet to be discovered, that these species are smaller, less abundant, and rarer than species that are already named and described [30], and are more prone to extinction by habitat loss and change [31].

Despite their manifold importance and declining trends, insects are often neglected in conservation planning and assessments [32, 33]. Only 0.12% of European insect species are protected by law [34]. While protected areas have become a key part of biodiversity conservation in safeguarding species from diverse anthropogenic and natural threats, insects have been rarely considered a focal species when designating protected areas [33], 76% of insect species are inadequately represented by the global protected area system [35], and protected areas failed to cover the full annual cycle of 84% migratory butterflies [36]. The situation is more extreme for tropical insects, as we possess a limited understanding of their distribution and the threat intensity. This lack of knowledge significantly hinders the development of effective national and global conservation plans [3, 17, 31], particularly in the tropics.

Here, we adopted multiple approaches to mitigate these limitations. First, we assembled a team of tropical ecologists with decades of experience across seven countries and five continents to get a global view. We developed a framework for identifying factors contributing to this tropical insect data gap and strategies to mitigate it. In the second part of the review, we apply this framework to Bangladesh as a representative tropical mega-populated country, where insect conservation will have a significant impact on biodiversity conservation as well as agricultural productivity and human well-being. This case study highlights how relatively simple measures can help ameliorate the situation.

Major knowledge shortfalls for tropical insects and potential solutions

Several factors contribute to the shortfall in our understanding of tropical insects. These include limited financial resources (e.g., funding gaps), technical barriers (e.g., national centres for insect studies, including museums, and inadequate infrastructure for DNA sequencing), and a shortage of skilled personnel (e.g., taxonomists, parataxonomists, and field collectors). Geographic challenges (e.g., the remoteness of regions such as the Amazon) and human conflict (e.g., war zones) further restrict research efforts. In some cases, knowledge exists but is not made accessible or integrated globally, and gaps in one area (e.g., unidentified species) can hinder progress in others (e.g., ecological research), exemplifying the Linnaean shortfall [22, 24]. We categorise these challenges into four main groups: global visibility, data shortfall, lack of infrastructure, and insufficient conservation action.

Issue I. Global visibility

For two primary reasons, much of the research done by tropical ecologists remains outside of the global knowledge base. First, many tropical biologists and natural historians publish in local journals, which are inaccessible to non-native researchers and international search systems, such as Web of Science or Scopus [37]. Hence, researchers, who depend solely on international search systems, miss research findings published in local journals during a global systematic review [37, 38]. Second, many tropical researchers publish in regional languages, which are mostly unavailable in international search systems and to English-speaking researchers and policy-makers [37]. For example, the best-known insect natural history journal in the UK is run by amateurs and called the Entomologist's Monthly Magazine, which has been publishing since 1864. This is full of records and updates for insect species in the UK. If this were published in another language and ignored, then British scientists would have a very poor understanding of their insect fauna!

Potential solution

Because many researchers from the tropics publish in regional journals or regional languages, limiting the synthesis to only English can severely bias our findings. For example, in a global study, the amount of conservation evidence increased by 12-25% geographically and 5-32% taxonomically after including a non-English language search [39]. It is crucial to consider non-English languages when searching for relevant studies [Table 1]. International collaboration, especially collaborating with local researchers, is essential to accessing non-English-language publications [3]. This is for two primary reasons. First, there can be multiple search systems in a non-English language, and knowing the most relevant and comprehensive one is essential. For example, both Airiti Library (https://www.airiti.com/en/One-Page/index.html) and CNKI (https://www.cnki.net/index/) are for Chinese language publications, but CNKI is the most comprehensive one [37]. Second, even though the automated translation process is advancing with time, English words translated into non-English languages and vice versa could have several meanings. For example, in Polish and German, 'biodiversity conservation' has many meanings [37].

Issue II. Data shortfall

Three primary factors contribute to the shortfalls in tropical insect data: a lack of systematic monitoring, limited participation in citizen science applications, and a shortage of taxonomists and access to collections and DNA analysis [Table 1]. Although the majority of insect species reside in the tropics, global biodiversity data are primarily from temperate regions [24]. Over the last few decades, citizen science has revolutionised biodiversity data collection, yet its contribution in the tropics is still minimal [40]. Nearly 30% of the distribution data from all sources for insects in the Global Biodiversity Information Facility (https://www.gbif.org/) is from the United Kingdom. In contrast, only 0.5% is from Brazil, despite Brazil being the most biodiverse country in the world and being approximately 35 times the size of the UK. Even for the UK, 84% of the insect distribution data is for Lepidoptera (butterflies and moths), reflecting the overwhelming interest in these insects from the general public. Such sampling bias is also prevalent in global-scale trend analysis. For example, van Klink et al. [15] is the most comprehensive meta-analysis on insect population trends; however, only a few of the 1,687 study sites were from the tropics, which limits our understanding of the status of tropical insects.

Finally, the number of taxonomists is substantially lower in the tropics, leading to Linnaean shortfalls. Even European countries, after 250 years of taxonomy, are nowhere near completing the description of the majority of temperate insect species [41]. In large Malaise-trapping programmes in some European countries and elsewhere, DNA barcoding of the samples have found that a large proportion of the species are undescribed (mostly in Diptera and Hymenoptera) [e.g., 42], have found, through DNA barcoding of the samples, that a large proportion of the species are undescribed (mostly in Diptera and Hymenoptera) [e.g., 42], thereby increasing estimates of the size of their faunas. A further major problem is taxonomic intractability; large parts of some groups are almost impossible to identify to species as the basic taxonomic framework has not been completed. For example, by assessing 10,097 tropical rainforest bark beetles, Stork et al. [30] identified 58 undescribed species, representing a 37% increase in the number of described species from Australia. As previously hypothesised [43], this study confirms that most undescribed species are smaller, less abundant, and range-restricted than described species.

Table 1. A framework on strategic conservation of tropical insects, highlighting the major limitations and the potential solutions to conserve tropical insects

Major limitation	Reasons behind the limitation	Potential solution
 Global visibility	• Most researchers publish in local journals and regional languages	Change in attitudes surrounding international collaborations
		Database on researchers and subject expertise in developing countries
		Database on research outputs
		Multilingual approach
	• Limited monitoring data Lack of participation	Insect monitoring through citizen science
		Long-term ecological monitoring schemes
		Skilled taxonomists with access to advanced tools (e.g., DNA barcoding) and collections

Data shortfall	in citizen science applications • Lack of expert taxonomic expertise and access to collections and DNA analysis	National biodiversity data repositories
		Projects on platforms such as iNaturalist (https://www.inaturalist.org) and Biodiversity Atlas – India (https://www.bioatlasindia.org), with a focus on native contributions
Lack of infrastructure	• Parachute science • Limited funding • Lack of expertise • Absence of powerful analysis tools	International collaborations
		Institutionally support the return of tropical ecologists to their native countries to undertake cutting-edge biodiversity research
		Active government support for biodiversity research, policy development, and conservation implementation
		Allocate specific grants, especially supporting long-term data collection
		Prioritise endemic/native/ threatened species
		Training of field scientists in field sampling, including novel sampling methods, insect preservation and curation
		Powerful data servers and training of native researchers in large-scale data analysis
Insufficient conservation actions	• Lack of specific conservation plans	Systematic conservation planning
		Prioritise sampling in areas not previously sampled
		Prioritise indicator species
		Scientifically sound, knowledge-based policy making
		Involve local communities and stakeholders

Potential solution

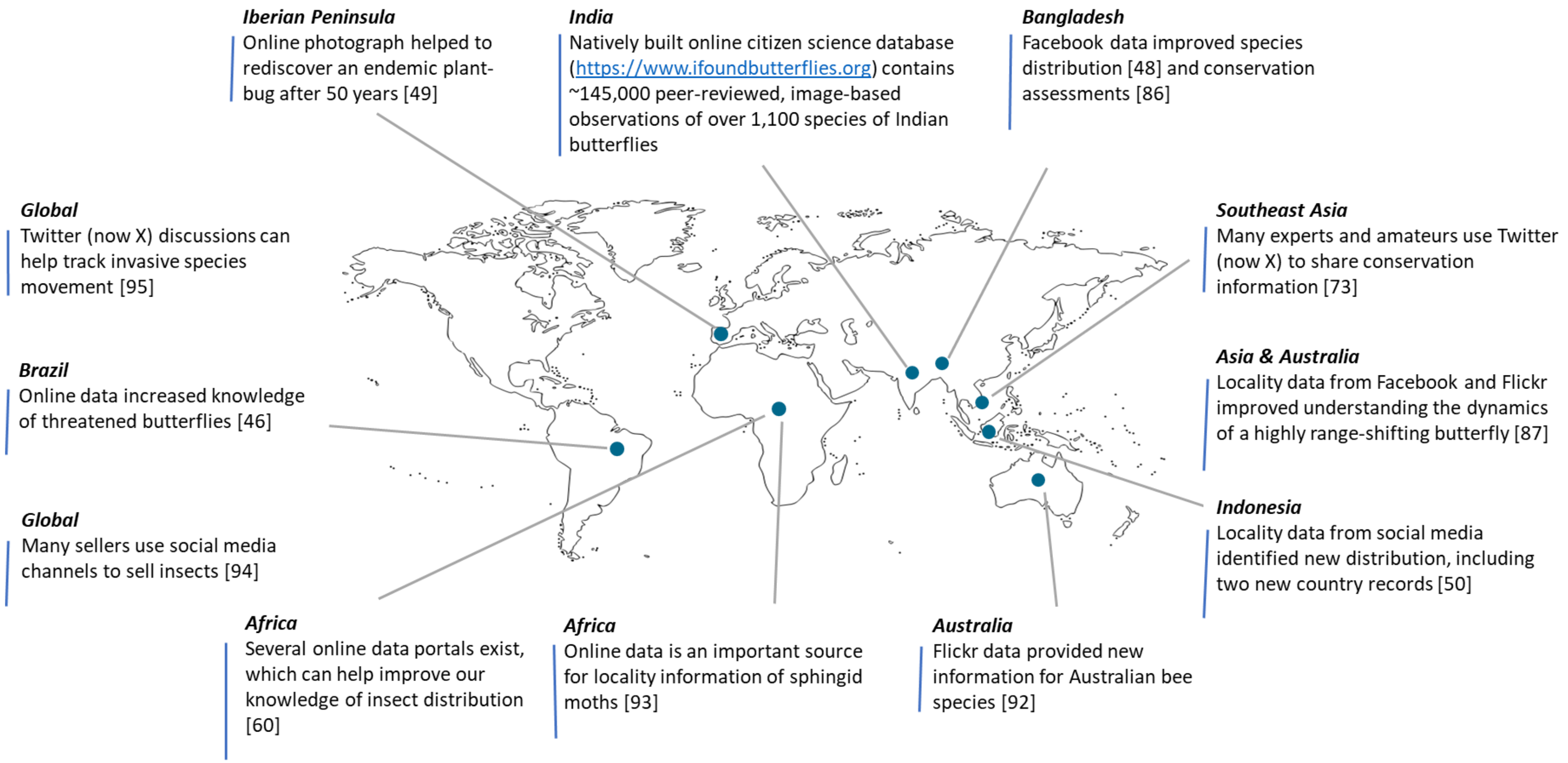
As many insect species are declining, addressing the tropical insect data shortfall is crucial for designing effective conservation policies and actions [3, 33]. To achieve this, we must identify both traditional and non-traditional data sources and create data repositories that visualise species distributions. Second, we need to utilise the power of community science. Researchers can't be everywhere simultaneously; however, community participation can help minimise such issues. For example, National Moth Week (https://nationalmothweek.org/) takes place annually during the last week of July. The main organisers work with the country representatives to arrange national-scale monitoring, and thousands share their moth observations. Similarly, parataxonomists (local assistants trained by professional biologists) can provide high-quality biological specimens and ecological information [44]. Participating in large-scale citizen science is necessary to address the insect data shortfall. Opportunistic citizen science observations can also improve range estimations for threatened species: 70% of the assessed Brazilian threatened butterflies' ranges were extended after adding opportunistic citizen science observations [45, 46].

Third, biodiversity observation data from online platforms can help minimise the data shortfall [47]. With the widespread availability of smartphones and fast internet, many people share photographs of insects on social media and other online platforms. However, the absence of an automated process for transferring this data means it does not get automatically deposited into the global biodiversity repositories [Box 1]. For instance, 86% of the threatened Bangladeshi butterfly species were only available on Facebook [48], although users can link their Facebook profile to iNaturalist to batch-import Facebook photographs. Similarly, online photographs contributed to the rediscovery of an endemic plant-bug *Parahypsitylus nevadensis* (Hemiptera: Miridae) after a 50-year absence in the Iberian Peninsula [49], and helped to obtain new species locality information and identify new insect species in Indonesia and India [50; Biodiversity Atlas – India (https://www.bioatlasindia.org/)]. We must utilise the considerable power of community science by initiating population monitoring schemes in the tropics (e.g., Indian Butterfly Monitoring Scheme (https://www.ibms-network.in), and monitoring schemes in Brazil and Singapore) and incorporate such data into national and global-scale data repositories, such as the Biodiversity Atlas – India and iNaturalist platforms (https://www.inaturalist.org). Finally, by combining citizen science with the rapid advancements in technologies (e.g., computer vision, acoustic monitoring, radar, molecular methods), we can improve insect data collection [3, 51, 52, 53, 54]. For example, computer vision can automatically identify insects; radar can track their movements. Although the process could be challenging because most insect species are small, technological advances would revolutionise insect distribution data [52, 53, 54].

Finally, the role of skilled and experienced taxonomists is vital, and more taxonomists are needed in the tropics. DNA barcoding can reveal large numbers of undescribed species, many of which could be cryptic and may only be separated using molecular methods. As citizens are not equipped to make the taxonomic decisions needed to identify cryptic species, it’s difficult for them to resolve the issue, but they can certainly improve the situation [55].

Box 1. The potential of online data to improve our understanding of tropical insect distribution.

Although systematic insect recording has been common in the temperate regions for centuries, it remains limited in tropical regions. However, the widespread use of mobile phones and fast internet is encouraging citizen scientists to share their biodiversity observations on online portals (e.g., social media, blog posts, citizen science platforms) that can be used in insect ecology and conservation. Such non-traditional community science data can be used to address diverse ecological questions, including minimising data shortfalls by identifying new species locality records, tracking invasive or pest species, and improving conservation assessments. To obtain the background data for this box, we searched Google Scholar [https://scholar.google.com/] by typing 'insect online data'.



Issue III. Lack of infrastructure

While most biodiversity hotspots are distributed in the tropics, they face intense human pressures due to high population density, rapid growth, and poverty [56]. These areas are disproportionately affected by armed conflicts, which further degrade ecosystems. Weak governance and corruption in many hotspot countries hinder effective conservation, highlighting the need to integrate social, political, and environmental strategies [57]. A considerable gap in the required infrastructure to record species is a major obstacle for tropical insect research [56, 58].

First, tropical countries are mostly underdeveloped, and their economic conditions are substantially lower than those in temperate countries [59, 60]. As a result, these countries often lack the funding necessary to prioritise biodiversity documentation and conservation. Second, security is a serious issue in many tropical countries. For example, armed conflicts are widespread in Central Africa due to political instability, leading to biodiversity recording as a *life-threatening* factor: even after being global hotspots, the amount of butterfly distribution data from such areas is scarce [60]. Third, insect collections in well-managed museums are rare in the tropics. Museum specimens can be used to track how insects respond to global changes; however, that is frequently impossible because of the lack of historical specimens. Moreover, technical support in museums is scarce, and the few hired staff have to spend their time maintaining collections, leaving little time for entering data into online databases. Fourth, analysing a large amount of insect data requires powerful machines and extensive knowledge of ecological modelling; however, such expertise and analytical tools are rare in the tropics. Consequently, they often cannot apply sophisticated analysis even after the collection of biodiversity data.

Finally, *parachute science* (also known as helicopter/colonial science) is a serious issue that shows inequity in research relationships between scientists from economically developed and developing countries [61, 62]. Researchers from developing countries are often treated as mere suppliers of collecting permits and tropical specimens rather than as equal collaborators, and they rarely get a prominent first or corresponding authorship or even adequate acknowledgement [62, 63, 64, 65]. This also needs to be remedied since contributions of local scientists will strengthen the conservation of tropical insects in those host countries.

Potential solution

Considering the limited opportunities for research funding, researchers and policy-makers must act strategically. Active participation of governments is necessary to have some applied outcomes for the research outputs and to prioritise research topics. For better use of funding, governments could prioritise studying endemic, native, or threatened insect species and allocate specific grants to work on their taxonomy and conservation. An excellent model for such a scheme is the Australian Biological Resources Study (ABRS), which for decades has provided support for the discovery, naming and classification of Australia's living organisms. This might not work long-term, as in many countries, threatened and non-threatened species face similar conservation challenges [e.g., 66]. International funding opportunities, such as multi-national collaboration, could be a potential solution in this case.

It is essential to establish insect museums to engage local researchers, facilitate species discovery and ecological research, and assess the long-term impacts of environmental changes. Such research museums could receive insect collections from private collectors and researchers, as seen in the Chau Chak Wing Museum in Sydney, Australia, and the McGuire Centre for Lepidoptera and Biodiversity at the Florida Museum of Natural History, USA. In Brazil, the donation of a private collection to the Museum of the University of Campinas resulted in the discovery of several important lost types of Brazilian butterflies [67]. In India, collaborative research involving professional and citizen scientists in a recently developed research collections has resulted in discovery of dozens of insect species (https://www.biodiversitycollections.in).

Researchers in developed countries should adopt a more collaborative approach with scientists in developing countries. This includes directly involving collaborators in research and promoting exchanges among researchers and students. Exchanges of this type often result in well-trained students who are keen to return their expertise to their home countries, with a direct impact on the development of local science and the formation of highly qualified human resources [64, 68]. If a tropical insect ecologist lacks skills in advanced research methodologies and requires a computing system, international collaboration could also help overcome such issues.

Establishing a national or international-scale database containing information about researchers and their outputs could help minimise this issue. For example, Earthwatch researchers (https://earthwatch.org/) compiled plant-pollinator interaction data from the La Selva Biological Research Station in Costa Rica from 1997 to 2018. Analysis of these data identified a decline in insect diversity and abundance, partly due to climate and weather anomalies [69]. Such an approach is vital to limit parachute science: effective, respectful and well-communicated cross-boundary collaboration with the local community and regional experts is needed. Yau et al. [70] assembled a team of butterfly experts, compiled species distribution data (from the experts and citizen science resources) for the entire South and Southeast Asia, and identified hotspots of butterfly distribution. Such methods can also be used to compile databases on species distribution and answer many ecological questions.

A long-term solution to the issue of limited native infrastructure and expertise is to provide institutional and government support for the return of tropical ecologists to their native countries, enabling them to undertake cutting-edge biodiversity research. For example, in India, the Ramanujan Fellowship programme funded by the Government of India provides salary and research funding to returning scientists (https://www.indiascienceandtechnology.gov.in/programme-schemes/research-and-development/ramanujan-fellowship). Similar programmes need to be expanded to other tropical countries to reverse the ‘brain-drain’ from developing countries to the western scientific powerhouses. Such returning scientists have placed China, India, and Brazil on a map of ecological institutions with prominent contributions to the research and conservation of tropical insects.

Issue IV. Insufficient conservation actions

Unlike vertebrates, conservation studies on insects are rare, and the situation is particularly dire in the tropics [33, 71, 72, 73]. In the last few decades, protected areas have become a crucial component of biodiversity conservation, particularly in safeguarding species from diverse threats [74]. However, 76% of insect species are inadequately represented by protected areas [35], tropical insects have been rarely considered in protected area designation, and most protected area studies on tropical insects are based on checklists and distribution patterns rather than on systematic population monitoring [33]. In a study in Brazil, approximately 41% of all occurrence records of threatened butterflies are found within fully protected areas [46]. In addition to such discrepancies, protected areas in the tropics are highly biased geographically. Due to population densities and economic insolvencies, many people live inside or surrounding protected areas and are directly or indirectly dependent on natural resources [75, 76]. Finally, conservation plans in the tropics rarely engage indigenous people and local communities, often contributing to failures of planned conservation outcomes [77, 78, but see 79].

Potential solution

To minimise the decline in tropical insects [17, 29, 80] and the consequences on humans and the ecosystems [1, 4], it is crucial to focus on their conservation. Given the lack of infrastructure (discussed in **Issue III**) and push for economic development, conserving all areas may be challenging. Therefore, we need to identify important conservation areas by prioritising species, also known as systematic conservation prioritisation [81, 82]. Instead of relying solely on publicly available biodiversity databases, such as GBIF, researchers should compile data from various additional sources, including social media, and regional experts and should make it publicly available so that others can access it. At every step of the conservation plan, verifying the data and outputs in collaboration with regional experts is essential [Figure 1]. For example, distribution data needs to be verified to check for any erroneous records. The distribution map and important conservation areas also need to be verified to assess whether any areas were missing from the model. Considering that the distribution of many species is changing in response to environmental changes, it is also important to consider time-sliced distribution maps in the model to minimise the potential impact and ensure efficient conservation. However, this approach may be challenging for most insect species due to the limited availability of distribution data. Once important conservation areas are identified, researchers must share their outputs with the agencies, decision-makers, such as government officials or conservation organisations [Figure 1B].

Case study from Bangladesh

To assess the feasibility of our proposed solutions, we examine the scenarios mentioned above for Bangladesh, a densely populated tropical country. Bangladesh has a population of 172 million and is 130th out of 193 countries, like neighbouring countries, India and Bhutan, in terms of its Human Development Index. Similar to many other nations, Bangladesh faces various anthropogenic threats that are causing rapid declines in many invertebrate and vertebrate species: 25% of the assessed species are listed as threatened in the national Red List [83]. Nevertheless, the global scientific community is largely unaware of the status of biodiversity in Bangladesh, primarily because many researchers publish their findings in local journals, systematic monitoring is rare, and citizen science applications are not widely adopted [48]. The IUCN Bangladesh carried out the first comprehensive assessment of the threat status of 305 butterfly species in 2015, establishing a crucial baseline for insect biodiversity in the country [83]. Since then, the recorded number of butterfly species in the country has increased to 421, prompting IUCN Bangladesh to initiate a new assessment effort [84]. In this context, we focus on butterflies as a case study, since they are the most well-known group of insects. Notably, 62% of the 305 assessed butterfly species are nationally threatened, making them the only insect taxon that has been evaluated [83]. Given the significant variety of habitats that different insect groups occupy and the lack of data for most of these groups, future research should investigate the applicability of our framework to other taxa. Expanding to ecologically distinct groups, such as beetles or bees, would help assess its generality and better align the framework's scope with its broader conservation aims.

I. Evidence synthesis

We followed three steps to compile published studies on Bangladesh's butterflies [Figure 2A; Supplemental Information]. We identified 111 relevant studies, of which only 34 were from international journals (listed in the Scimago journal ranking; https://www.scimagojr.com/), highlighting the importance of local journals and expert elicitation. Approximately 91% of the studies were published after 2010 [Figure 2B], especially after the publication of the first pictorial handbook on the butterflies of Bangladesh [85]. It indicates that the study of butterflies in Bangladesh is a relatively recent phenomenon. The studies were widely distributed; however, most studies were from the major cities [e.g., Dhaka (centre), Sylhet (northeast), Chittagong (southeast); Figure 2C].

Because Bangladesh's butterfly data are poorly known, researchers have identified many new species in recent years, and 45% of the published studies described species new to the country [Figure 2D-F]. The new species were mainly recorded from Sylhet (northeast) and Chittagong (southeast), and within and surrounding the national parks, highlighting the importance of protected areas. Several new species were recorded from different university campuses (e.g., Jahangirnagar University, Chittagong University).

Following Chowdhury et al. [33], we grouped the published studies into four broad categories [Supplemental Table S1] to understand the publication bias [Figure 2F]. Nearly 65% of the studies were on range distributions [i.e., checklists, new regional records] and only three were on conservation. It highlights a significant conservation gap in Bangladesh, like many other developing countries.

II. Distribution data

Similar to many tropical countries, distribution data for Bangladeshi insects are poorly represented in global biodiversity repositories. A random search in GBIF indicates that there are only 10,000 distribution records with coordinate uncertainty of < 10,000 m for all insect species of Bangladesh, and < 3% were from iNaturalist [accessed on 1 May 2025]. However, many people share their biodiversity observations on social media platforms, such as Facebook, and this non-traditional online data can help reduce the data shortfall [e.g., 48, 50]. For example, by compiling species locality data from Facebook and GBIF, Chowdhury et al. [48] showed that 266 species were from Facebook and 125 from GBIF. In addition, 167 of 169 threatened species from Facebook, whereas 59 threatened species from GBIF, and 143 of the 145 unique species (species found in either of the two databases) were from Facebook, whereas only two unique species from GBIF [Figure 3A, B; 48]. Combining such online data with GBIF data improved conservation assessments for butterflies [86] and helped understand the rapid expansion of a range-shifting butterfly [87].

III. Threat assessment

Understanding how natural and anthropogenic threats impact tropical insects is challenging because long-term monitoring data are extremely scarce [but see 18]. However, compiling data from multiple sources can help address this issue. For example, Chowdhury [88] compiled distribution data for the butterflies of Bangladesh from GBIF, social media, published resources, and personal observations, and assessed how the suitability of their current distribution might change with climate change. The future climatic conditions may be unsuitable for 2-34% of species, the mean direction of suitable habitats could be 196° [Figure 3C], and the mean elevation of suitable habitats could increase by 238% [88]. Geographically, most areas in Bangladesh are characterised by lower elevational gradients, which may lead to the local extinction of 42% of butterfly species [88].

IV. Conservation planning

To safeguard species from diverse threats, they require high-quality conservation areas, which have led to the emergence of the concept of protected areas. However, as in many other tropical countries, Bangladesh's protected areas were not selected using modern systematic conservation approaches [33, 66, 75]. As a result, species are poorly represented in the current protected area system. In Bangladesh, only one of the 226/305 assessed butterfly species (*Euploea crameri nicevillei*) is adequately represented by the current protected area system [Figure 3D]. Bangladesh must protect at least 27% of the area to conserve all butterfly species adequately [Figure 3E; 66], which is slightly below the target [30%] set by the Kunming-Montreal Global Biodiversity Framework, to which Bangladesh is a signatory [66, 89]. Regular updates to the Red List of Butterflies of Bangladesh are vital for monitoring species and population trends. Additionally, establishing butterfly parks (by planting butterfly-friendly plants), promoting ecotourism at butterfly hotspots, and organising butterfly fairs will enhance conservation planning and efforts across the country [84].

Concluding remarks

Insect decline poses a key global threat [4 12, 90]. However, most insect studies are on temperate regions, which account for < 20% of insect species, highlighting a large tropical insect data shortfall. Such biases can severely affect the conservation status of most tropical insect species. Therefore, it is crucial to act promptly and develop an integrated approach to address this issue [29, 91]. We provide evidence that we must involve regional experts to understand and address the problem of data shortfall. We must start long-term field monitoring in the tropics and supplement that by extracting evidence from non-English languages and online data portals. Our framework will help in reducing the data shortfall, improving conservation assessments, and meeting the targets of the Kunming-Montreal Global Biodiversity Framework.

Acknowledgements

AVLF thanks CNPq (304291/2020-0), and the Fundação de Amparo à Pesquisa do Estado de São Paulo-FAPESP (grant 2021/03868-8). KK's work on Indian insect biodiversity has been supported over the years by a Ramanujan Fellowship from the Government of India and research grants from the NCBS.

References

1. Stork, N. E. (2018). How many species of insects and other terrestrial arthropods are there on Earth?. *Annual Review of Entomology*, 63(2018), 31-45.

2. Basset, Y., Lamarre, G. P., Donoso, D. A., Souto-Vilarós, D., Perez, F., Bobadilla, R., ... & Barrios, H. (2025). The magnitude of cryptic insect diversity in one tropical rainforest. bioRxiv, 2025-02.

3. Slade, E. M., & Ong, X. R. (2023). The future of tropical insect diversity: strategies to fill data and knowledge gaps. *Current Opinion in Insect Science*, 58, 101063.

4. Wagner, D. L. (2020). Insect declines in the Anthropocene. *Annual Review of Entomology*, 65(1), 457-480.

5. Wilson, E. O. (1987). The little things that run the world (the importance and conservation of invertebrates). *Conservation Biology*, *1*, 344-346.

6. Williams, B. A., Venter, O., Allan, J. R., Atkinson, S. C., Rehbein, J. A., Ward, M., ... & Watson, J. E. (2020). Change in terrestrial human footprint drives continued loss of intact ecosystems. *One Earth*, 3(3), 371-382.

7. Sloan, S., Jenkins, C. N., Joppa, L. N., Gaveau, D. L., & Laurance, W. F. (2014). Remaining natural vegetation in the global biodiversity hotspots. *Biological Conservation*, *177*, 12-24.

8. Keck, F., Peller, T., Alther, R., Barouillet, C., Blackman, R., Capo, E., ... & Altermatt, F. (2025). The global human impact on biodiversity. *Nature* (in press), 1-6. https://doi.org/10.1038/s41586-025-08752-2.

9. Halsch, C. A., Elphick, C. S., Bahlai, C. A., Forister, M. L., Wagner, D. L., Ware, J. L., & Grames, E. M. (2025). Meta-synthesis reveals interconnections among apparent drivers of insect biodiversity loss. *BioScience*, biaf034.

10. Dirzo, R., Young, H. S., Galetti, M., Ceballos, G., Isaac, N. J., & Collen, B. (2014). Defaunation in the Anthropocene. *Science*, 345(6195), 401-406.

11. Powney, G. D., Carvell, C., Edwards, M., Morris, R. K., Roy, H. E., Woodcock, B. A., & Isaac, N. J. (2019). Widespread losses of pollinating insects in Britain. *Nature Communications*, *10*(1), 1-6.

12. Wagner, D. L., Grames, E. M., Forister, M. L., Berenbaum, M. R., & Stopak, D. (2021). Insect decline in the Anthropocene: Death by a thousand cuts. *Proceedings of the National Academy of Sciences*, 118(2), e2023989118.

13. Harvey, J. A., Tougeron, K., Gols, R., Heinen, R., Abarca, M., Abram, P. K., ... & Chown, S. L. (2023). Scientists' warning on climate change and insects. *Ecological Monographs*, 93(1), e1553.

14. Hallmann, C. A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., ... & De Kroon, H. (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PloS One*, 12(10), e0185809.

15. Van Klink, R., Bowler, D. E., Gongalsky, K. B., Swengel, A. B., Gentile, A., & Chase, J. M. 2020. Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances. *Science*, 368(6489), 417-420.

16. Edwards, C. B., Zipkin, E. F., Henry, E. H., Haddad, N. M., Forister, M. L., Burls, K. J., ... & Schultz, C. B. (2025). Rapid butterfly declines across the United States during the 21st century. *Science*, 387(6738), 1090-1094.

17. Boyle, M. J., Bonebrake, T. C., Dias da Silva, K., Dongmo, M. A., Machado França, F., Gregory, N., ... & Ashton, L. A. (2025). Causes and consequences of insect decline in tropical forests. *Nature Reviews Biodiversity* (in press), 1-17. https://doi.org/10.1038/s44358-025-00038-9.

18. Sharp, A., Boyle, M., Bonebrake, T., Guo, Y., Kitching, R., Stork, N., Zeng, X., & Ashton, L. Stronger El Niños reduce tropical forest arthropod diversity and function. *Nature* (in press).

19. Saunders, M. E., Janes, J. K., & O'Hanlon, J. C. (2020). Moving on from the insect apocalypse narrative: engaging with evidence-based insect conservation. *BioScience*, 70(1), 80-89.

20. Cooke, R., Outhwaite, C. L., Bladon, A. J., Millard, J., Rodger, J. G., Dong, Z., ... & Isaac, N. J. (2025). Integrating multiple evidence streams to understand insect biodiversity change. *Science*, 388(6742), eadq2110.

21. Mammola, S., Riccardi, N., Prié, V., Correia, R., Cardoso, P., Lopes-Lima, M., & Sousa, R. (2020). Towards a taxonomically unbiased European Union biodiversity strategy for 2030. *Proceedings of the Royal Society B*, *287*(1940), 20202166.

22. Cardoso, P., Erwin, T. L., Borges, P. A., & New, T. R. (2011). The seven impediments in invertebrate conservation and how to overcome them. *Biological Conservation*, *144*(11), 2647-2655.

23. Collen, B., Ram, M., Zamin, T., & McRae, L. 2008. The tropical biodiversity data gap: addressing disparity in global monitoring. *Tropical Conservation Science*, 1(2), 75-88.

24. Hortal, J., De Bello, F., Diniz-Filho, J. A. F., Lewinsohn, T. M., Lobo, J. M., & Ladle, R. J. (2015). Seven shortfalls that beset large-scale knowledge of biodiversity. *Annual Review of Ecology, Evolution, and Systematics*, 46(1), 523-549.

25. Pinkert, S., Farwig, N., Kawahara, A. Y., & Jetz, W. (2025). Global hotspots of butterfly diversity are threatened in a warming world. *Nature Ecology & Evolution* (in press), 1-12. https://doi.org/10.1038/s41559-025-02664-0.

26. Outhwaite, C. L., McCann, P., & Newbold, T. (2022). Agriculture and climate change are reshaping insect biodiversity worldwide. *Nature*, 605(7908), 97-102.

27. Lister, B. C., & Garcia, A. (2018). Climate-driven declines in arthropod abundance restructure a rainforest food web. *Proceedings of the National Academy of Sciences*, 115(44), E10397-E10406.

28. Willig, M. R., Woolbright, L., Presley, S. J., Schowalter, T. D., Waide, R. B., Heartsill Scalley, T., ... & Lugo, A. E. (2019). Populations are not declining and food webs are not collapsing at the Luquillo Experimental Forest. *Proceedings of the National Academy of Sciences*, 116(25), 12143-12144.

29. Janzen, D. H., & Hallwachs, W. (2021). To us insectometers, it is clear that insect decline in our Costa Rican tropics is real, so let's be kind to the survivors. *Proceedings of the National Academy of Sciences*, 118(2), e2002546117.

30. Stork, N. E., Boyle, M. J., Wardhaugh, C., & Beaver, R. A. (2024). What can an analysis of Australian tropical rainforest bark beetles suggest about the missing millions of Earth's insect species?. *Insect Conservation and Diversity*, 17(6), 1156-1166.

31. Boyle, M. J., Sharp, A. C., Barclay, M. V., Chung, A. Y., Ewers, R. M., de Rougemont, G., ... & Ashton, L. A. 2024. Tropical beetles more sensitive to impacts are less likely to be known to science. *Current Biology*, 34(16), R770-R771.

32. Basset, Y., & Lamarre, G. P. (2019). Toward a world that values insects. *Science*, 364(6447), 1230-1231.

33. Chowdhury, S., Jennions, M. D., Zalucki, M. P., Maron, M., Watson, J. E., & Fuller, R. A. (2023). Protected areas and the future of insect conservation. *Trends in Ecology & Evolution*, 38(1), 85-95.

34. Leandro, C., Jay-Robert, P., & Vergnes, A. (2017). Bias and perspectives in insect conservation: a European scale analysis. *Biological Conservation*, *215*, 213-224.

35. Chowdhury, S., Zalucki, M. P., Hanson, J. O., Tiatragul, S., Green, D., Watson, J. E., & Fuller, R. A. (2023). Three-quarters of insect species are insufficiently represented by protected areas. *One Earth*, 6(2), 139-146.

36. Chowdhury, S., Cardillo, M., Chapman, J. W., Green, D., Norris, D. R., Riva, F., ... & Fuller, R. A. (2025). Protected area coverage of the full annual cycle of migratory butterflies. *Conservation Biology*, e14423.

37. Chowdhury, S., Gonzalez, K., Aytekin, M. Ç. K., Baek, S. Y., Bełcik, M., Bertolino, S., ... & Amano, T. (2022). Growth of non-English-language literature on biodiversity conservation. *Conservation Biology*, *36*(4), e13883.

38. Martín-Martín, A., Orduna-Malea, E., Thelwall, M., & López-Cózar, E. D. (2018). Google Scholar, Web of Science, and Scopus: A systematic comparison of citations in 252 subject categories. *Journal of Informetrics*, 12(4), 1160-1177.

39. Amano, T., Berdejo-Espinola, V., Christie, A. P., Willott, K., Akasaka, M., Báldi, A., ... & Sutherland, W. J. (2021). Tapping into non-English-language science for the conservation of global biodiversity. *PLoS Biology*, 19(10), e3001296.

40. Troudet, J., Grandcolas, P., Blin, A., Vignes-Lebbe, R., & Legendre, F. (2017). Taxonomic bias in biodiversity data and societal preferences. *Scientific Reports*, *7*(1), 9132.

41. Ronquist, F., Forshage, M., Häggqvist, S., Karlsson, D., Hovmöller, R., Bergsten, J., ... & Gärdenfors, U. (2020). Completing Linnaeus's inventory of the Swedish insect fauna: Only 5,000 species left?. *PloS One*, *15*(3), e0228561.

42. Buchner, D., Sinclair, J. S., Ayasse, M., Beermann, A. J., Buse, J., Dziock, F., ... & Leese, F. (2025). Upscaling biodiversity monitoring: Metabarcoding estimates 31,846 insect species from Malaise traps across Germany. *Molecular Ecology Resources*, *25*(1), e14023.

43. Scheffers, B. R., Joppa, L. N., Pimm, S. L., & Laurance, W. F. (2012). What we know and don't know about Earth's missing biodiversity. *Trends in Ecology & Evolution*, *27*(9), 501-510.

44. Basset, Y., Novotny, V., Miller, S. E., Weiblen, G. D., Missa, O., & Stewart, A. J. (2004). Conservation and biological monitoring of tropical forests: the role of parataxonomists. *Journal of Applied Ecology*, *41*, 163-174.

45. Rosa, A. H., Ribeiro, D. B., & Freitas, A. V. (2023). How data curation and new geographical records can change the conservation status of threatened Brazilian butterflies. *Journal of Insect Conservation*, 27(3), 403-414.

46. Rosa, A. H., & Freitas, A. V. (2024). The role of citizens in conservation science: a case study with threatened Brazilian butterflies. *Journal of Insect Conservation*, 28(6), 1149-1160.

47. Jarić, I., Correia, R. A., Brook, B. W., Buettel, J. C., Courchamp, F., Di Minin, E., ... & Roll, U. (2020). iEcology: harnessing large online resources to generate ecological insights. *Trends in Ecology & Evolution*, 35(7), 630-639.

48. Chowdhury, S., Aich, U., Rokonuzzaman, M., Alam, S., Das, P., Siddika, A., ... & Callaghan, C. T. (2023). Increasing biodiversity knowledge through social media: A case study from tropical Bangladesh. *BioScience*, 73(6), 453-459.

49. Goula, M., Sesma, J. M., & Vivas, L. (2013). Photosharing websites may improve Hemiptera biodiversity knowledge and conservation. *ZooKeys*, (319), 93.

50. Suprayitno, N., Narakusumo, R. P., von Rintelen, T., Hendrich, L., & Balke, M. (2017). Taxonomy and Biogeography without frontiers–WhatsApp, Facebook and smartphone digital photography let citizen scientists in more remote localities step out of the dark. *Biodiversity Data Journal*, (5), e19938.

51. Tan, M. K. (2021). Soundscape of urban-tolerant crickets (Orthoptera: Gryllidae, Trigonidiidae) in a tropical Southeast Asia city, Singapore. *Bioacoustics*, 30(4), 469-486.

52. Van Klink, R., August, T., Bas, Y., Bodesheim, P., Bonn, A., Fossøy, F., ... & Bowler, D. E. (2022). Emerging technologies revolutionise insect ecology and monitoring. *Trends in Ecology & Evolution, 37(10), 872-885*.

53. Sheard, J. K., Adriaens, T., Bowler, D. E., Büermann, A., Callaghan, C. T., Camprasse, E. C., ... & Bonn, A. (2024). Emerging technologies in citizen science and potential for insect monitoring. *Philosophical Transactions of the Royal Society B*, 379(1904), 20230106.

54. Jain, A., Cunha, F., Bunsen, M. J., Cañas, J. S., Pasi, L., Pinoy, N., ... & Rolnick, D. (2024, September). *Insect identification in the wild: The AMI dataset*. In European Conference on Computer Vision (pp. 55-73). Cham: Springer Nature Switzerland.

55. Slater-Baker, M. R., Fagan-Jeffries, E. P., Oestmann, K. J., Portmann, O. G., Bament, T. M., Howe, A. G., ... & Fernández-Triana, J. (2025). DNA barcoding, integrative taxonomy, citizen science, and Bush Blitz surveys combine to reveal 34 new species of Apanteles (Hymenoptera, Braconidae, Microgastrinae) in Australia. *ZooKeys*, 1227, 1.

56. Stork, N. E., & Habel, J. C. (2014). Can biodiversity hotspots protect more than tropical forest plants and vertebrates?. *Journal of Biogeography*, *41*(3), 421-428.

57. Smith, R. J., Muir, R. D., Walpole, M. J., Balmford, A., & Leader-Williams, N. (2003). Governance and the loss of biodiversity. *Nature*, *426*(6962), 67-70.

58. Barrett, P. S. (1999). The limits of democracy: Socio-political compromise and regime change in post-Pinochet Chile. *Studies in Comparative International Development*, *34*(3), 3-36.

59. Liu, X., Li, X., Shi, H., Yan, Y., & Wen, X. (2021). Effect of economic growth on environmental quality: Evidence from tropical countries with different income levels. *Science of the Total Environment*, 774, 145180.

60. Dongmo, M. A., Hanna, R., & Bonebrake, T. C. (2023). Enhancing scientific and community capacity to conserve Central African Lepidoptera. *Biological Conservation*, 279, 109938.

61. Asase, A., Mzumara-Gawa, T. I., Owino, J. O., Peterson, A. T., & Saupe, E. (2022). Replacing "parachute science" with "global science" in ecology and conservation biology. *Conservation Science and Practice*, 4(5), e517.

62. Miller, J., White, T. B., & Christie, A. P. (2023). Parachute conservation: Investigating trends in international research. *Conservation Letters*, 16(3), e12947.

63. Jarić, I., Diagne, C., & Chowdhury, S. (2025). Moving beyond continents for global and inclusive science. *Frontiers in Ecology and the Environment*, 23, e2851.

64. Da, W., Rana, S. K., Bawa, K., Kunte, K., & Wang, Z. (2025). Roof of the world: Home and border in the genomic era. *Molecular Ecology Resources*, *25*(2), e13827.

65. World Bank. (2014). "A decade of development in sub- Saharan African science, technology, engineering and mathematics research (English)" (World Bank Group and Elsevier, 2014); https://documents.worldbank.org/curated/en/237371468204551128/A-decade-of-development-in-sub-Saharan-African-science-technologyengineering-and-mathematics-research.

66. Chowdhury, S., Fuller, R. A., Rokonuzzaman, M., Alam, S., Das, P., Siddika, A., ... & Hanson, J. O. (2023). Insights from citizen science reveal priority areas for conserving biodiversity in Bangladesh. *One Earth*, 6(10), 1315-1325.

67. Siewert, R. R., Rosa, A. H. B., Lamas, G., & Freitas, A. V. L. (2023). Lost and Found: Taxonomic Notes on Some Butterflies (Lepidoptera: Papilionoidea) from JF Zikán found on F. Dissmann's Collection. *Neotropical Entomology*, *52*(1), 1-4.

68. Wang, Z., Hanley, N., Kwak, J., Vari-Lavoisier, I., Al Hussein, M., Tyson, L. S., ... & Chankseliani, M. (2024). How do international student returnees contribute to the development of their home countries? A systematic mapping and thematic synthesis. *International Journal of Educational Research*, *125*, 102330.

69. Salcido, D. M., Forister, M. L., Garcia Lopez, H., & Dyer, L. A. (2020). Loss of dominant caterpillar genera in a protected tropical forest. *Scientific Reports*, 10(1), 422.

70. Yau, E. Y. H., Jones, E. E., Tsang, T. P. N., Xing, S., Corlett, R. T., Roehrdanz, P., ... & Bonebrake, T. C. (2025). Spatial occurrence records and distributions of tropical Asian butterflies. *Scientific Data*, *12*(1), 1-13.

71. Cardoso, P., Barton, P. S., Birkhofer, K., Chichorro, F., Deacon, C., Fartmann, T., ... & Samways, M. J. (2020). Scientists' warning to humanity on insect extinctions. *Biological Conservation*, 242, 108426.

72. Duffus, N. E., Echeverri, A., Dempewolf, L., Noriega, J. A., Furumo, P. R., & Morimoto, J. (2023). The present and future of insect biodiversity conservation in the neotropics: policy gaps and recommendations. *Neotropical Entomology*, 52(3), 407-421.

73. Ong, X. R., Tan, B., Chang, C. H., Puniamoorthy, N., & Slade, E. M. (2025). Identifying the Knowledge and Capacity Gaps in Southeast Asian Insect Conservation. *Ecology Letters*, 28(1), e70038.

74. Gaston, K. J., Jackson, S. F., Cantú-Salazar, L., & Cruz-Piñón, G. (2008). The ecological performance of protected areas. *Annual Review of Ecology, Evolution, and Systematics*, *39*(1), 93-113.

75. Chowdhury, S., Alam, S., Labi, M. M., Khan, N., Rokonuzzaman, M., Biswas, D., ... & Fuller, R. A. (2022). Protected areas in South Asia: Status and prospects. *Science of the Total Environment*, 811, 152316.

76. Coad, L., Campbell, A., Miles, L., & Humphries, K. (2008). The costs and benefits of protected areas for local livelihoods: a review of the current literature. UNEP World Conservation Monitoring Centre, Cambridge, UK.

77. Mbanze, A. A., Ribeiro, N. S., da Silva, C. V., & Santos, J. L. (2019). An expert-based approach to assess the potential for local people engagement in nature conservation: The case study of the Niassa National Reserve in Mozambique. *Journal for Nature Conservation*, 52, 125759.

78. Dawson, N. M., Coolsaet, B., Sterling, E. J., Loveridge, R., Gross-Camp, N. D., Wongbusarakum, S., ... & Rosado-May, F. J. (2021). The role of Indigenous peoples and local communities in effective and equitable conservation. *Ecology and Society*, 26(3), 19.

79. Joshi, P., Dahanukar, N., Bharade, S., Dethe, V., Dethe, S., Bhandare, N., & Watve, M. (2021). Combining payment for crop damages and reward for productivity to address wildlife conflict. *Conservation Biology*, *35*(6), 1923-1931.

80. Lewinsohn, T. M., Agostini, K., Lucci Freitas, A. V., & Melo, A. S. (2022). Insect decline in Brazil: an appraisal of current evidence. *Biology Letters*, 18(8), 20220219.

81. Margules, C. R., & Pressey, R. L. (2000). Systematic conservation planning. *Nature*, 405(6783), 243-253.

82. Giakoumi, S., Richardson, A. J., Doxa, A., Moro, S., Andrello, M., Hanson, J. O., ... & Katsanevakis, S. (2024). Advances in systematic conservation planning to meet global biodiversity goals. *Trends in Ecology & Evolution*, 40(4), 395-410.

83. IUCN Bangladesh. (2015). *Red list of Bangladesh: A brief on assessment result 2015*. International Union for Conservation of Nature, Bangladesh Country Office.

84. Hossain, M.M. (2023). A review on the diversity of butterfly (Insecta: Lepidoptera) fauna from Bangladesh. *Bangladesh J. Zool*. 51(1): 03-34.

85. Chowdhury, S. H., Hossain, M. (2011). *Butterflies of Bangladesh: A Pictorial Handbook*. Skylark Printers.

86. Chowdhury, S., Fuller, R. A., Ahmed, S., Alam, S., Callaghan, C. T., Das, P., ... & Bonn, A. (2024). Using social media records to inform conservation planning. *Conservation Biology*, *38*(1), e14161.

87. Chowdhury, S., Hawladar, N., Roy, R. C., Capinha, C., Cassey, P., Correia, R. A., ... & Bonn, A. (2024). Harnessing social media data to track species range shifts. *EcoEvoRXiv*. https://doi.org/10.32942/X2R63N.

88. Chowdhury, S. (2023). Threatened species could be more vulnerable to climate change in tropical countries. *Science of the Total Environment*, *858*, 159989.

89. Convention on Biological Diversity (CBD). (2022). *Kunming–Montreal Global biodiversity framework*. Draft decision submitted by the President CBD/COP/15/L.25, 18 December 2022. https://www.cbd.int/conferences/2021-2022/cop-15/documents.

90. Goulson, D. (2019). The insect apocalypse, and why it matters. *Current Biology*, *29*(19), R967-R971.

91. Kawahara, A. Y., Reeves, L. E., Barber, J. R., & Black, S. H. (2021). Eight simple actions that individuals can take to save insects from global declines. *Proceedings of the National Academy of Sciences*, 118(2), e2002547117.

92. ElQadi, M. M., Dorin, A., Dyer, A., Burd, M., Bukovac, Z., & Shrestha, M. (2017). Mapping species distributions with social media geo-tagged images: Case studies of bees and flowering plants in Australia. *Ecological Informatics*, 39, 23-31.

93. Ballesteros-Mejia, L., Kitching, I. J., Jetz, W., Nagel, P., & Beck, J. (2013). Mapping the biodiversity of tropical insects: species richness and inventory completeness of African sphingid moths. *Global Ecology and Biogeography*, 22(5), 586-595.

94. Gippet, J. M., George, L., & Bertelsmeier, C. (2022). Local coexistence of native and invasive ant species is associated with micro-spatial shifts in foraging activity. *Biological Invasions*, 24(3), 761-773.

95. Daume, S. (2016). Mining Twitter to monitor invasive alien species—An analytical framework and sample information topologies. *Ecological Informatics*, 31, 70-82.

List of Figures

Figure 1. A framework on strategic conservation of tropical insects. A) some common issues and solutions when working with tropical insects, and B) how typical conservation assessments or planning should be conducted for tropical insects.

Figure 2. The status of published studies on the butterflies of Bangladesh. A) the three steps of reviews for the butterflies of Bangladesh, B) the growth of studies by year, C) the geographic bias, D) the growth in recording new species for the country, E) the geographic distribution of the new species, and F) publication bias.

Figure 3. The status of the butterflies of Bangladesh. A) four steps of compiling the location data, B) the potential of location data obtained from Facebook, C) the potential changes in habitat suitability, highlighting the range shift in degrees, D) the performance of the current protected areas in covering the geographic range, where DD is Data Deficient, LC is Least Concern, VU is Vulnerable, CR is Critically Endangered, and EN is Endangered, and E) the most important conservation areas, identified using the conservation prioritisation approach.

Figure 1

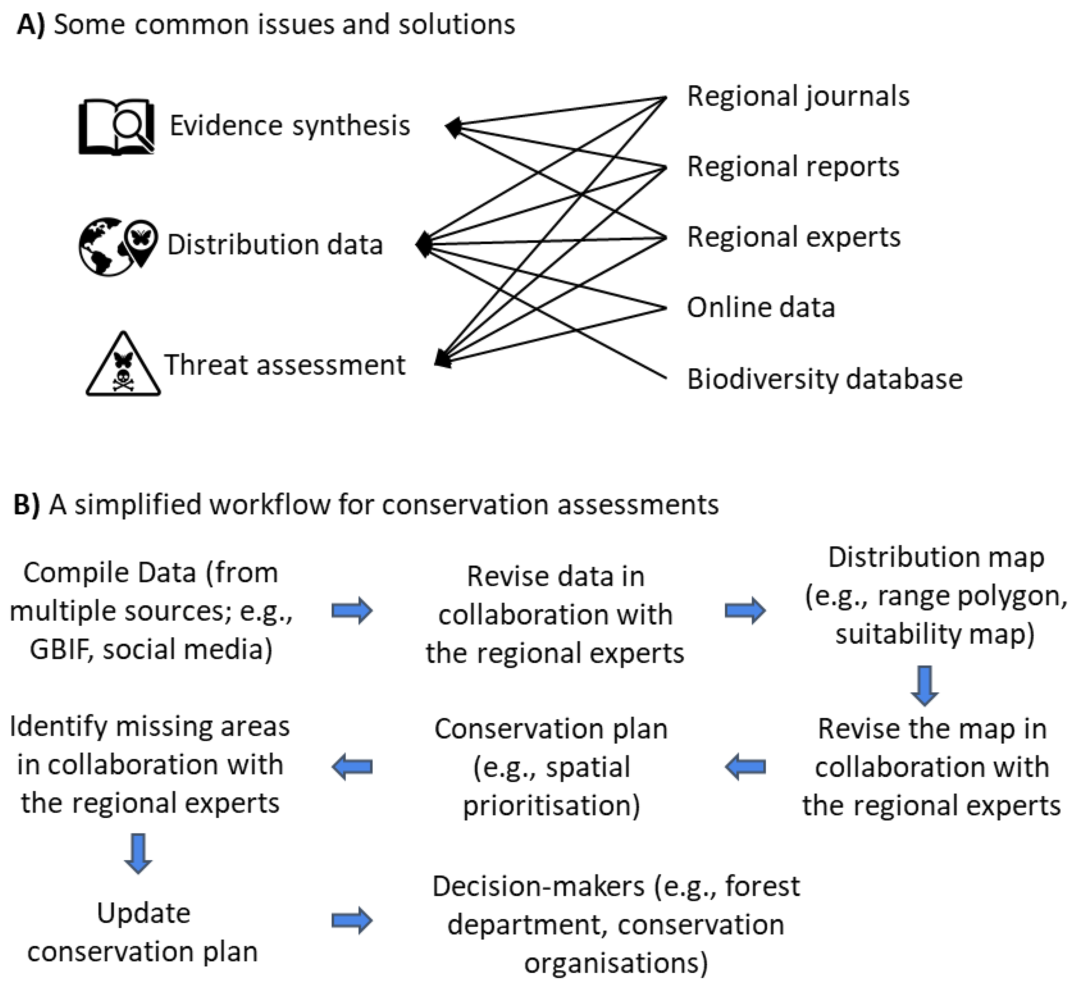

A) Some common issues and solutions
Evidence synthesis
Distribution data
Threat assessment
Regional journals
Regional reports
Regional experts
Online data
Biodiversity database
B) A simplified workflow for conservation assessments
Compile Data (from multiple sources; e.g., GBIF, social media)
Revise data in collaboration with the regional experts
Distribution map (e.g., range polygon, suitability map)
Revise the map in collaboration with the regional experts
Conservation plan (e.g., spatial prioritisation)
Identify missing areas in collaboration with the regional experts
Update conservation plan
Decision-makers (e.g., forest department, conservation organisations)

Figure 2

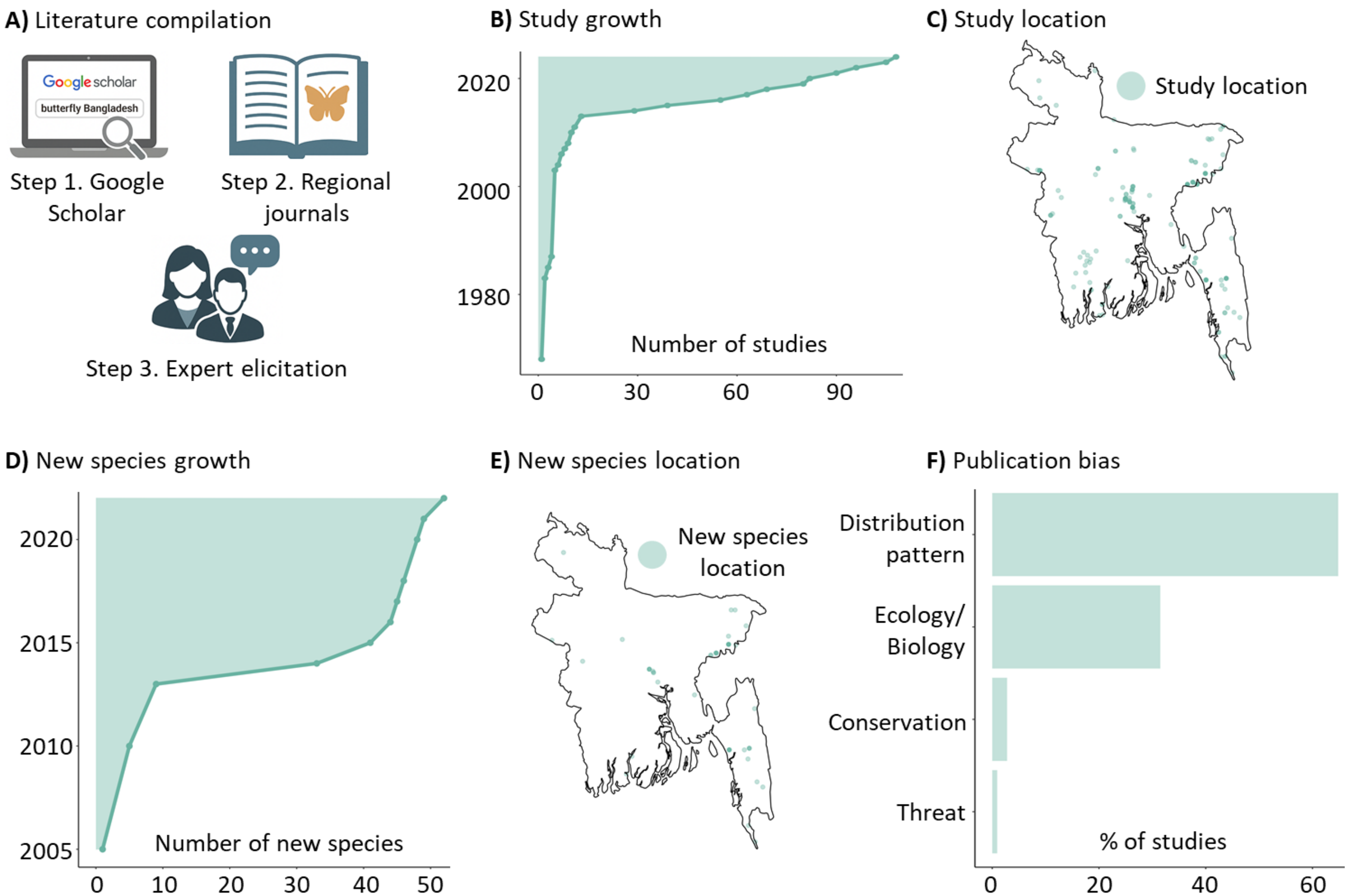
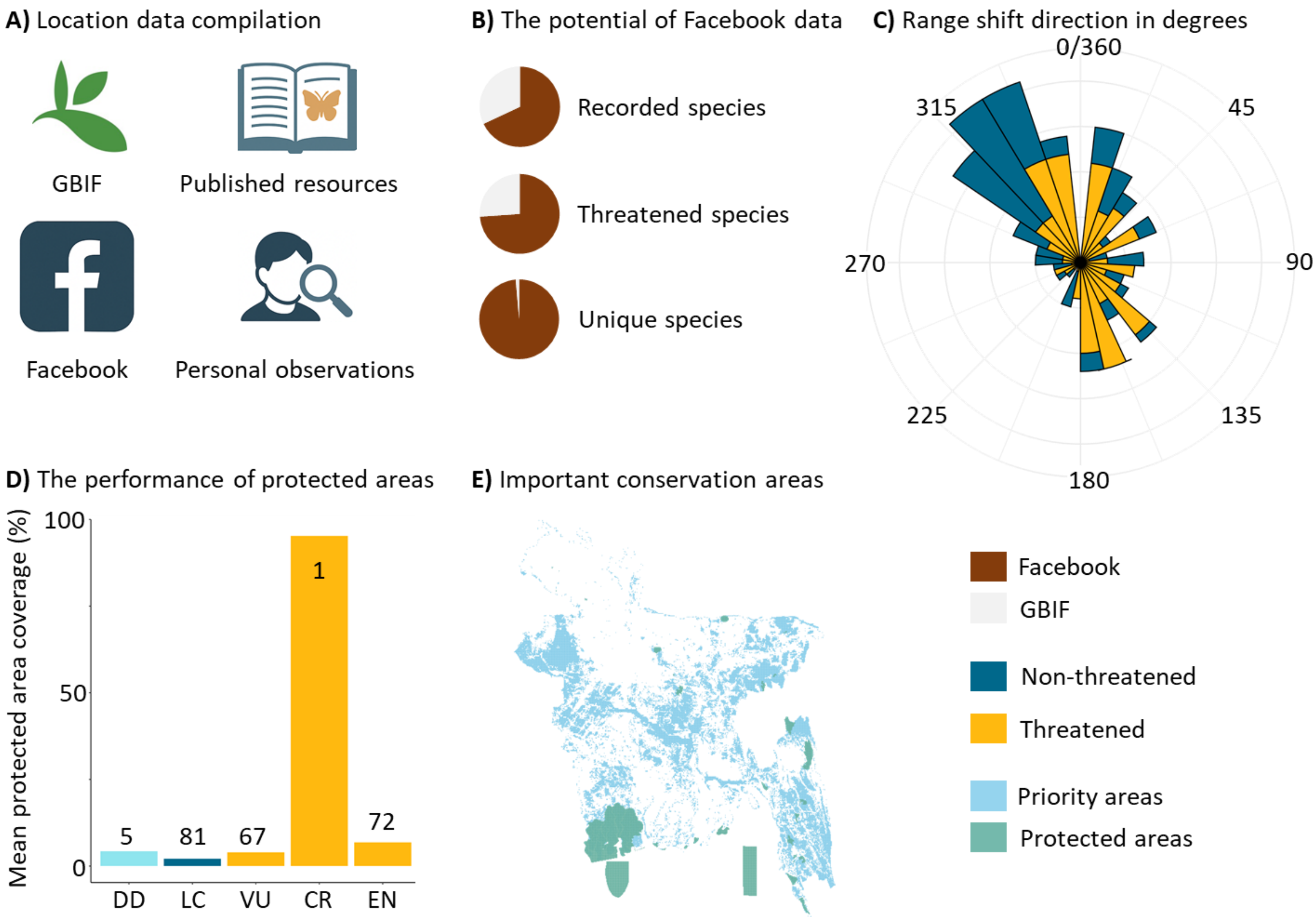

A) Literature compilation
Google scholar
butterfly Bangladesh
Step 1. Google Scholar
Step 2. Regional journals
Step 3. Expert elicitation
B) Study growth
2020
2000
1980
Number of studies
0
30
60
90
C) Study location
Study location
D) New species growth
2020
2015
2010
2005
Number of new species
0
10
20
30
40
50
E) New species location
New species location
F) Publication bias
Distribution pattern
Ecology/ Biology
Conservation
Threat
% of studies
0
20
40
60

Figure 3


A) Location data compilation
GBIF
Published resources
Facebook
Personal observations
B) The potential of Facebook data
Recorded species
Threatened species
Unique species
C) Range shift direction in degrees
0/360
45
90
135
180
225
270
315
D) The performance of protected areas
Mean protected area coverage (%)
100
50
0
5
81
67
1
72
DD
LC
VU
CR
EN
E) Important conservation areas
Facebook
GBIF
Non-threatened
Threatened
Priority areas
Protected areas

Supplemental Information

Strategic conservation of tropical insects

Shawan Chowdhury*[1a,b,c], Syeda F Jahan[2], Perpetra Akite[3], Yanina Benedetti[4], Timothy Bonebrake[5], André VL Freitas[6], Md M Hossain[7], Richard J Ladle[8], Federico Morelli[4,9], Nigel Stork[10], Krushnamegh Kunte[11]

* corresponding author

[1]dr.shawanchowdhury@gmail.com; https://orcid.org/0000-0003-2936-5786
[1a]School of Biological Sciences, Monash University, Melbourne, VIC, Australia
[1b]Czech University of Life Sciences Prague, Faculty of Environmental Sciences, Kamýcká 129, CZ-165 00 Prague 6, Czech Republic
[1c]Biodiversity Society, 49/1 Babar Road, Dhaka 1207, Bangladesh

[2]Department of Zoology, University of Dhaka, Dhaka, Bangladesh; sfjahan5@gmail.com;

[3]College of Natural Sciences, Makerere University, Kampala, Uganda; perpetra.akite@gmail.com; https://orcid.org/0000-0002-0302-1822

[4]Czech University of Life Sciences Prague, Faculty of Environmental Sciences, Kamýcká 129, CZ-165 00 Prague 6, Czech Republic; ybenedetti73@gmail.com; https://orcid.org/0000-0003-1600-2310

[5]School of Biological Sciences, The University of Hong Kong, Pokfulam, Hong Kong SAR, CN; tim.bonebrake@gmail.com; https://orcid.org/0000-0001-9999-2254

[6]Departamento de Biologia Animal and Museu de Diversidade Biológica, Instituto de Biologia, Universidade Estadual de Campinas, Campinas, São Paulo, Brazil; baku@unicamp.br; https://orcid.org/0000-0002-5763-4990

[7]Department of Zoology, Jahangirnagar University, Dhaka 1342, Bangladesh; monwarbutterfly@gmail.com; https://orcid.org/0000-0002-4380-7280

[8]Institute of Biological and Health Sciences, Federal University of Alagoas, Maceió, Brazil; richardjamesladle@gmail.com; https://orcid.org/0000-0003-3200-3946

[9]Institute of Biological Sciences, University of Zielona Góra, Zielona Góra, Poland; fmorellius@gmail.com; https://orcid.org/0000-0003-1099-1357 fmorellius@gmail.com; https://orcid.org/0000-0003-1099-1357

[10]School of Environment and Science, Griffith University, Nathan, Queensland, Australia; nigel.stork@griffith.edu.au; https://orcid.org/0000-0001-7812-2452

[11]National Centre for Biological Sciences (NCBS), Tata Institute of Fundamental Research (TIFR), GKVK Campus, Bellary Road, Bengaluru 560065, India; krushnamegh@ncbs.res.in; https://orcid.org/0000-0002-3860-6118

Literature review

We took three different approaches to compiling butterfly studies from Bangladesh. First, we searched Google Scholar (https://scholar.google.com./) by typing 'butterfly Bangladesh'. We chose Google Scholar over Web of Science or Scopus because it performs significantly better than other international search systems in retrieving regional studies [1]. We checked all the available search pages until we found a page that did not contain any studies on the butterflies of Bangladesh. Before screening the full papers, we carefully read the abstract for each paper and only included papers that focused on the butterflies of Bangladesh. Second, we searched Bangladesh's most popular local journal, Bangladesh Journal of Zoology (https://www.banglajol.info/index.php/BJZ), run by the Zoological Society of Bangladesh. Considering that many researchers might have published in journals that are unavailable online, we talked to the regional butterfly experts (SC, MMH).

Overall, we identified 140 relevant studies. From each study, we extracted publication information (journal name, article type, year), location, threats (if any highlighted in the study), the performance of protected areas, and conservation assessment information. We converted the location information into Longitude and Latitude using Google Maps (https://www.google.com/maps).

Supplementary Table S1. Classification of study types, obtained from Chowdhury et al. [2].

Study type	Description
Distribution	Published/described checklist, new species, distribution pattern, or predicted suitable habitat.
Conservation	Discussed PA management, or the importance of ecological network, buffer zone, connectivity between PAs, etc.
Threat	Focused primarily on different types of threats [e.g., climate change) on the available species.
Ecology/Biology	Focused on the Ecology/Biology of species

References

1. Chowdhury, S., Gonzalez, K., Aytekin, M. Ç. K., Baek, S. Y., Bełcik, M., Bertolino, S., ... & Amano, T. (2022). Growth of non-English-language literature on biodiversity conservation. Conservation Biology, 36(4), e13883.

2. Chowdhury, S., Jennions, M. D., Zalucki, M. P., Maron, M., Watson, J. E., & Fuller, R. A. (2023). Protected areas and the future of insect conservation. *Trends in Ecology & Evolution*, 38(1), 85-95.