FORESTGEO ARTHROPOD INITIATIVE
ANNUAL REPORT 2020

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I. BACKGROUND AND PARTICIPATING FORESTGEO SITES

The 'ForestGEO Arthropod Initiative' aims at monitoring key arthropod assemblages over long-term and studying insect-plant interactions over the network of the Forest Global Earth Observatories (ForestGEO, https://forestgeo.si.edu/research-programs/arthropod-initiative). The Initiative integrates with ongoing monitoring of plant dynamics within the ForestGEO network, causes minimum possible impact to the plots and focus on a priority set of assemblages chosen for their ecological relevance, taxonomic tractability and ease of sampling. At each participating ForestGEO site, the first years of the program are usually devoted to a 'baseline' survey. The baseline survey is followed by longer-term programs of field work and analysis, organized into two main sub-programs: monitoring, and key interaction studies. The monitoring sub-program is directed to detecting long-term changes, as reflected in priority assemblages, driven by climatic cycles, climatic change and landscape scale habitat alteration. Monitoring protocols are derived from those used during the baseline survey. The food web approach of interaction studies targets interactions between plants and specific insect assemblages, with different protocols than those used for monitoring.

So far, the Arthropod Initiative involves seven ForestGEO sites: Yasuni in Ecuador, Barro Colorado Island (BCI) in Panama, Khao Chong (KHC) in Thailand, Tai Po Kau (Hong Kong), Dinghushan and Xishuangbanna (XTBG) in China and Wanang (WAN) in Papua New Guinea. At BCI, four full-time research assistants were in charge of arthropod monitoring protocols in 2020: Filonila Perez, Ricardo Bobadilla, Yacksecari Lopez and Alejandro Ramirez. The program coordinator, YB, doubled as BCI site supervisor. The collections and staff of the ForestGEO Arthropod Initiative in Panama are based at the Tupper complex.

Most of the insect monitoring at KHC in 2020 was under the responsibility of Montarika Panmeng, Manat Reungaew, Kanyakarn Sripila, Sontaya Promchaisri, Sutipun Putnaul and Tassanai Kaewyod. Supervision at KHC was assured by Sarayudh Bunyavejchewin, Nantachai Pongpattananurak, (Kasetsart University, Bangkok), Watana Sakchoowong (Thai National Parks Wildlife and Plant Conservation Dept) and YB. At WAN, Francesca Dem (Binatang Research Centre), Vojtech Novotny (Czech Academy of Sciences and University of South Bohemia) and YB supervised assistants Roll Liplip, Ruma Umari, Fidelis Kimberg and Ananias Kamam, who were in charge of ForestGEO protocols. At Yasuni David Donoso (Escuela Politécnica Nacional, Quito, Ecuador) and assistants performed Winkler protocols to monitor litter ants, while Maria Fernanda Checa and Sebastian Mena (Museo QCAZ de Invertebrados. Pontificia Universidad Católica del Ecuador) organized butterfly transects. Timothy Bonebrake and Chum-Lim Luk supervised butterfly monitoring at the plots of Tai Po Kau, and Dingshushan. At Xishuangbanna, Aki Nakamura (Xishuangbanna Botanical Gardens) supervised butterfly, ant, fruitfly and termite monitoring.

In 2020, the covid pandemic affected differently insect monitoring at these sites. While monitoring at the sites of KHC and WAN was little affected, monitoring could not be organized at all at Yasuni and at the three Chinese sites. At BCI, monitoring data were collected but often not at the usual dates scheduled. We will probably need to use correcting factors to report insect abundance and other variables in 2020, so that time series are aligned with their starting year in 2009. When needed, this will be achieved by considering past results 2009-2019. In short, the integrity and continuity of the BCI data have been preserved. In Panama, staff of the ForestGEO Arthropod Initiative have been teleworking for most of 2020.

II. TAXONOMIC STUDIES AND DNA BARCODING

Alejandro Ramirez is improving the taxonomy of the reduviids of BCI as part of his MSc at the University of Panama. José Palacios-Vargas and his team at the Laboratorio de Ecología y Sistemática de Microartrópodos (UNAM, Mexico) have started publishing several papers about the Collembola fauna of BCI, in relation with our soil metabarcoding project (see published papers in 2020). Michel Laguerre and Benoit Vincent refined Arctiinae taxonomy for BCI, to support several manuscripts in preparation for this group. Apart from these taxonomic efforts, 2020 was quiet because the covid pandemic restricted mailing of specimens abroad (agencies delivering export permits did not or were slow to handle new requests). Instead we rather focused our attention on cleaning existing records, using our pictures and DNA barcodes in our databases. For example, for BCI, 310 species names (out of 2,474) were changed during 2020 (12.5%). This results from taxonomic analysis of specimens, new matches with molecular data or synonyms, or changes in the taxonomic hierarchy.

We consolidated our DNA barcoding data (+13,000 sequences available in projects ABCI, AKHC and AWAN). YB got new funding from the SI barcoding opportunity but work on this project has not started yet, because STRI laboratories are officially closed, due to the pandemic. We initiated different pilot projects related to DNA metabarcoding on BCI. All together these various sample represent > 7 GB of data in the platform mBrave that we have started analyzing. The first of a series of papers has been accepted for publication in *Metabarcoding and Metagenomics* (see publication list). DNA metabarcoding should help us one day to efficiently monitor most of arthropod species on BCI and at other sites.

III. MONITORING: BARRO COLORADO ISLAND, KHAO CHONG AND WANANG

Year 2020 represented the twelve year of insect monitoring at BCI. So far, the BCI database contains data on 623,462 arthropods, including 2,474 focal species (1,806 of which with pictures, 73%) and 70,475 pinned specimens in our collections (275 drawers). Each year we collect at BCI 330 insect samples (80 light trap samples, 50 Winkler samples, 120 butterfly transects, 40 termite transects and 40 bee bait samples) and in 2020 this represented 29,175 arthropods. However, due to the pandemic and to date, the data of only 220 out of 330 samples (67%) have been uploaded into our arthropod database. We expect to absorb this backload by early 2021.

Work on insect thermal tolerance with Greg Lamarre's team based in Gamboa (University of South Bohemia : Benita Laird-Hopkins (PhD student), Petr Blažek and Richard Ctvrtecka) was greatly disrupted in 2020 since, apart from Greg, our colleagues could not travel to Panama as planned. A few data were collected by the intern Stephany Arizala Cobo before the beginning of the pandemic and she is thanked here for her excellent work.

2020 represented our tenth year of monitoring at KHC. We collected 370 insect samples (80 light trap samples, 50 Winkler samples, 120 butterfly transects, 40 termite transects and 80 McPhail samples). So far, our database includes 228,660 specimens (36,329 pinned specimens in collections) and 2,458 focal species. We still need to improve on processing quickly insect samples and including representative insect pictures in our database. At WAN, 2020 represented the eighth year of insect monitoring. The ForestGEO insect database contains data on 80,000 specimens, but apart from butterflies and fruitflies, few of these specimens are yet identified.

YB co-authored with +75 renowned entomologists the article "A roadmap for insect conservation and recovery", which was published in early 2020 in *Nature Ecology and Evolution*. We reproduce the integrality of the article in Appendix I.

IV. INTERACTION STUDIES

We are still in the process of analyzing data resulting from the study of seed predators and herbivore damage on seedlings at the three sites of BCI, KHC and WAN. These studies were funded by the Grant Agency of the Czech Republic and result from a collaboration with Sofia Gripenberg (University of Reading), Owen Lewis (University of Oxford), Richard Ctvrtecka; Philip Butterill, Leonardo Ré Jorge (University of South Bohemia) and Simon Segar (Harper Adams University). The first phase of these projects (seed predators) is nearly complete with the submission of one manuscript to *Oikos* (see papers in preparation) and 6 papers published in 2019. The other phase monitored the survivorship of seedlings in control plots and in plots treated with insecticide, to evaluate the action of insect herbivores on seedlings. Richard Ctvrtecka is helping YB to database all the results and our seedling damage database includes now + 4 mio records. We expect to start analyzing these impressive data soon.

We slowly started our new project with the Grant Agency of the Czech Republic, entitled "Integrating genomic and trophic information into long-term monitoring of tropical insects: pollinators on Barro Colorado Island, Panama". Ernesto Bonadies was hired as PhD student collaborating with this project, and is supervised by YB, Greg Lamarre and Daniel Souto. Unfortunately, the project was much delayed by the pandemic as it proved difficult to collect, export and process specimens.

V. FORESTGEO ARTHROPOD DATABASE

The web version of the ForestGEO Arthropod database, which will essentially mirror snapshots of data for the sites of BCI, KHC and WAN, is ready and undergoing final security tests in Washington. The pandemic has been delaying final tests, but it should be on-line soon. The database and related web pages will allow to foster scientific collaboration via a better visibility of the ForestGEO Arthropod Initiative. Next year we plan to include in the database the insect seed predator data, which represent over 80,000 insect records with hostplant information. The current web pages of the ForestGEO Arthropod Initiative are at https://forestgeo.si.edu/research-programs/arthropod-initiative. The personal web page of the program coordinator is maintained at https://stri.si.edu/scientist/yves-basset. A new web site presenting the research activities of YB and collaborators is in construction.

VI. SCIENTIFIC OUTPUT

In 2020, the ForestGEO Arthropod Initiative trained, at the sites of BCI, KHC and WAN, 14 assistants (4: BCI, 6: KHC, 4: WAN); 1 intern (BCI); one MsSc student (BCI) and two PhD students (BCI). Collectively, we wrote 12 publications in 2020, including one in *Nature Ecology and Evolution*. More and more colleagues are interested in the work of the ForestGEO Arthropod Initiative and this is reflected by a steady growth in the number of annual publications (Plate I, item 11). We hope that the “new normal” of 2021 will allow us to pursue our monitoring and research programs without much difficulty, as well as starting new collaborations leading to an increasing number of exciting publications.

Publications related to the ForestGEO Arthropod Initiative in 2020:

Basset, Y., Donoso, D.A., Hajibabaei, M., Wright, M.T.G., Perez, K.H.J., Lamarre, G.P.A., De León, L.F., Palacios-Vargas, J.G., Castaño-Meneses, G., Rivera, R., Perez, F., Bobadilla, R., Lopez, Y., Ramirez, J.A. & Barrios, H. 2020. Methodological considerations for monitoring soil/litter arthropods in tropical rainforests using DNA metabarcoding, with a special emphasis on ants, springtails and termites. *Metabarcoding and Metagenomics,* **4**, 151-163.

Basset, Y., Palacios-Vargas, J.G., Donoso, D.A., Castaño-Meneses, G., Decaëns, T., Lamarre, G.P., De León, L.F., Rivera, M., García-Gómez, A., Perez, F., Bobadilla, R., Lopez, Y., Ramirez, J.A., Cruz, M.M., Galván, A.A., Mejía-Recamier, B.E. & Barrios, H. 2020. Enemy-free space and the distribution of ants, springtails and termites in the soil of one tropical rainforest. *European Journal of Soil Biology*, **99**, 103193.

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Davies, S.J, Abiem, I., Salim, K.A., Aguilar, S., Allen, D., Alonso, A., Anderson-Teixeira, K., Andrade, A., Arellano, G., Ashton, P.S., Baker, P.J., Baker, M.E., Baltzer, J.L., Basset, Y.,…, Zuleta, D. 2020. ForestGEO: understanding forest diversity and dynamics through a global observatory. *Biological Conservation*, in press.

Didham, R.K., Basset, Y., Collins, M., Leather, S.R.., Littlewood. N.A., Menz, M.H.M., Müller, J., Packer, L., Saunders, M.E., Schönrogge, K., Stewart, A.J.A., Yanoviak, S.P. & Hassall, C. 2020. Interpreting insect declines: seven challenges and a way forward. *Insect Conservation and Diversity*, **13**, 103-114.

Finnie, S., Sam, K., Leponce, M., Basset, Y., Drew, D., Schutze, M.K., Dahl, C., Damag, M., Dilu, M., Gewa, B., Kaupa, B., Keltim, M., Koane, B., Kua, J., Lilip, R., Mogia, M., Philip, F., Ray, B., Sam, L., Tulai, S., Uma, C., Umari, R., Valeba, J., Yalang, J. & Novotny, V. 2020. Assemblages of fruit flies (Diptera: Tephritidae) along an elevational gradient in the rainforests of Papua New Guinea. *Insect Conservation and Diversity*, in press.

Harvey, J.A., Heinen, R., Armbrecht, I. Basset, Y., … & de Kroon, H. 2020. International scientists formulate a roadmap for insect conservation and recovery. Nature Ecology and Evolution, **4**, 174-176.

Lamarre, G.P.A., Fayle T.M., Segar, S.T., Laird-Hopkins, B., Nakamura, A., Souto-Vilarós,D., Watanabe, S. & Basset, Y. 2020. Monitoring tropical insects in the 21st century. *Advances in Ecological Research*, **62**, 295-330.

Landry, B., Basset, Y., Hebert, P.D.N., & Maes, J.-M. 2020. On the Pyraloidea fauna of Nicaragua. *Tropical Lepidoptera Research*, 30, 93-102.

Leponce, L., Pascal, O., Basset, Y. & Novotny, V. 2020. Organizing large-scale inventories of biodiversity in the tropics: the genesis and lessons of the project Our Planet Reviewed Papua New Guinea – land component, in Robillard, T., Legendre, F., Villemant, C. & Leponce, M. (eds), Insects of Mount Wilhelm, Papua New Guinea - Volume 2. Muséum National d’Histoire Naturelle, Paris. *Mémoires du Muséum National d’Histoire Naturelle*, **214**, 11-40.

Palacios-Vargas, J.G. (2020). *Acheroxenylla* (Collembola, Hypogastruridae), first record from the Americas with description of a new species from a Peruvian cave. *Subterranean Biology*, **34**, 109–119.

Palacios-Vargas, J.G., Callohuari, Y.T. (2020). A new species of the genus *Neotropiella* Handschin, 1942 (Collembola: Neanuridae) from Peru. *Biodiversity Data Journal*, 8, e57743.

Other publications of the program coordinator in 2020:

This year all publications from YB were related to the ForestGEO Arthropod Initiative.

Selected manuscripts in preparation related to the ForestGEO Arthropod Initiative:

Host specificity and interaction networks of insects feeding on seeds and fruits in tropical rainforests. Submitted to *Oikos*.

Orchid bee communities show 50 years of stasis in protected tropical forest. Submitted to *Ecology*.

Towards long-term monitoring of soil invertebrates in the tropics: a DNA metabarcoding approach. Submitted to *Molecular Ecology Resources.*

Functional groups of rhinoceros beetles (Coleoptera, Dynastinae) in Panama.

Recent and current population dynamics of Neotropical tiger moths under climate changes and extreme anomalies.

Functional classification of Neotropical tiger moths: A perspective on vulnerability to climate change.

Long-term population trends of adult Lepidoptera in a tropical forest: Barro Colorado Island, Panama.

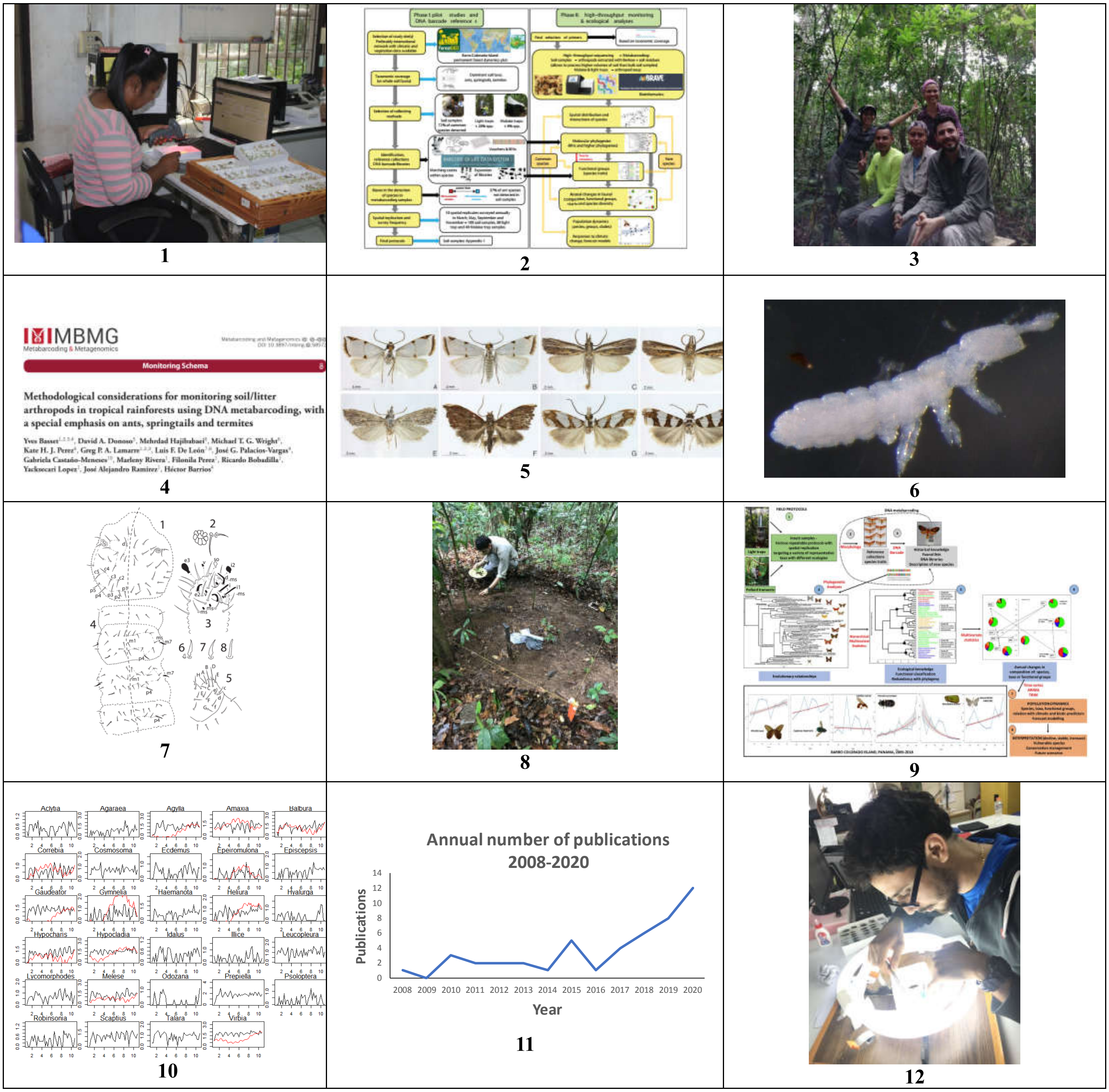
Long-term monitoring of social insects in tropical rainforests.

Calibrating biodiversity for long-term monitoring: detecting changes in assemblage composition from temporarily and spatially variable insect data.

Invasive ants in the Yasuni National Park. Where do they come from?

Ant male flights in a Neotropical seasonal forest are shaped by low relative humidity and not by rainfall or moonlight

Plate I. Representative activities/items for the ForestGEO Arthropod Initiative in 2020. (1) Montarika Panmeng (Tim) scanning specimen labels at Khao Chong. (2) Conceptual figure explaining the project of monitoring soil arthropods by DNA metabarcoding at BCI. (3) The ForestGEO team in Panama, who secured the integrity of BCI data in 2020, in often difficult conditions (Lopez, Bobadilla, Perez, Arizala Cobo, Ramírez). (4) Title page of our first paper entirely dedicated to DNA metabarcoding. (5) Nicaraguan Crambinae (see Landry et al., 2020). Pyraloidea represents a challenging group and we estimate that 500 species may be present on BCI. (6-7) *Willemia panamensis*, a new Collembola species among others described from BCI; habitus and taxonomic characteristics. Source: Garcia-Gomez & Palacios-Vargas, *Zootaxa*, **4674**, 564-570 (2019). (8) J. A. Ramírez working in a termite quadrat at BCI. (9) Figure indicating the workflow of the ForestGEO Arthropod Initiative, as explained in Lamarre et al. (2020), who provide a sound summary of the aims, methods and achievements of the Initiative. (10) Time series of arctiine genera at BCI.(11) Growth of the annual number of publications for the ForestGEO Arthropod Initiative, 2008-2020. (12) J. A. Ramírez preparing a specimen of Reduviidae.



APPENDIX I. FULL TEXT OF HARVEY ET AL. (2020) (see next page).

correspondence

International scientists formulate a roadmap for insect conservation and recovery

To the Editor — A growing number of studies are providing evidence that a suite of anthropogenic stressors — habitat loss and fragmentation, pollution, invasive species, climate change and overharvesting — are seriously reducing insect and other invertebrate abundance, diversity and biomass across the biosphere[1–8]. These declines affect all functional groups: herbivores, detritivores, parasitoids, predators and pollinators. Insects are vitally important in a wide range of ecosystem services[9] of which some are vitally important for food production and security (for example, pollination and pest control)[10]. There is now a strong scientific consensus that the decline of insects, other arthropods and biodiversity as a whole, is a very real and serious threat that society must urgently address[11–13]. In response to the increasing public awareness of the problem, the German government is committing funds to combat and reverse declining insect numbers[13]. This funding should act as a clarion call to other nations across the world — especially wealthier ones — to follow suit and to respond proactively to the crisis by addressing the known and suspected threats and implementing solutions.

We hereby propose a global 'roadmap' for insect conservation and recovery (Fig. 1). This entails the immediate implementation of several 'no-regret' measures (Fig. 1, step 1) that will act to slow or stop insect declines. Among the initiatives we encourage are the following immediate measures:

Taking aggressive steps to reduce greenhouse gas emissions; reversing recent trends in agricultural intensification including reduced application of synthetic pesticides and fertilizers and pursuing their replacement with agro-ecological measures; promoting the diversification and maintenance of locally adapted land-use techniques; increasing landscape heterogeneity through the maintenance of natural areas within the landscape matrix and ensuring the retention and creation of microhabitats within habitats which may be increasingly important for insects during extreme climatic events such as droughts or heatwaves; reducing identified local threats such as light, water or noise pollution, invasive species and so on; prioritizing the import of goods that are not produced at the cost of healthy, species-rich ecosystems; designing and deploying policies (for example, subsidies and taxation) to induce the innovation and adoption of insect-friendly technologies; enforcing stricter measures to reduce the introduction of alien species, and prioritizing nature-based tactics for their (long-term) mitigation; compiling and implementing conservation strategies for species that are vulnerable, threatened or endangered; funding educational and outreach programs, including those tailored to the needs of the wider public, farmers, land managers, decision makers and conservation professionals; enhancing 'citizen science' or 'community science' as a way of obtaining more data on insect diversity and abundance as well as engaging the public, especially in areas where academic or professional infrastructure is lacking; devising and deploying measures across agricultural and food value chains that favour insect-friendly farming, including tracking, labelling, certification and insurance schemes or outcome-based incentives that facilitate behavioural changes, and investing in capacity building to create a new generation of insect conservationists and providing knowledge and skills to existing professionals (particularly in developing countries).

To better understand changes in insect abundance and diversity, research should aim to prioritize the following areas:

Quantifying temporal trends in insect abundance, diversity and biomass by extracting long-term datasets from existing insect collections to inform new censuses; exploring the relative contributions of different anthropogenic stressors causing insect declines within and across different taxa; initiating long-term studies comparing insect abundance and diversity in different habitats and ecosystems along a management-intensity gradient and at the intersection of agricultural and natural habitats; designing and validating insect-friendly techniques that are effective, locally relevant and economically sound in agriculture, managed habitats and urban environments; promoting and applying standardized monitoring protocols globally and establishing long-term monitoring plots or sites based on such protocols, as well as increasing support for existing monitoring efforts; establishing an international governing body under the auspices of existing bodies (for example, the United Nations Environment Programme (UNEP) or the International Union for Conservation of Nature (IUCN)) that is accountable for documenting and monitoring the effects of proposed solutions on insect biodiversity in the longer term; launching public–private partnerships and sustainable financing initiatives with the aim of restoring, protecting and creating new vital insect habitats as well as managing key threats; increasing exploration and research to improve biodiversity assessments, with a focus on regional capacity building in understudied and neglected areas, and performing large-scale assessments of the conservation status of insect groups to help define priority species, areas and issues.

Most importantly, we should not wait to act until we have addressed every key knowledge gap. We currently have enough information on some key causes of insect decline to formulate no-regret solutions whilst more data are compiled for lesser-known taxa and regions and long-term data are aggregated and assessed. Implementation should be accompanied by research that examines impacts, the results of which can be used to modify and improve the implementation of effective measures. Furthermore, such a 'learning-by-doing' approach ensures that these conservation strategies are robust to newly emerging pressures and threats. We must act now. ❐

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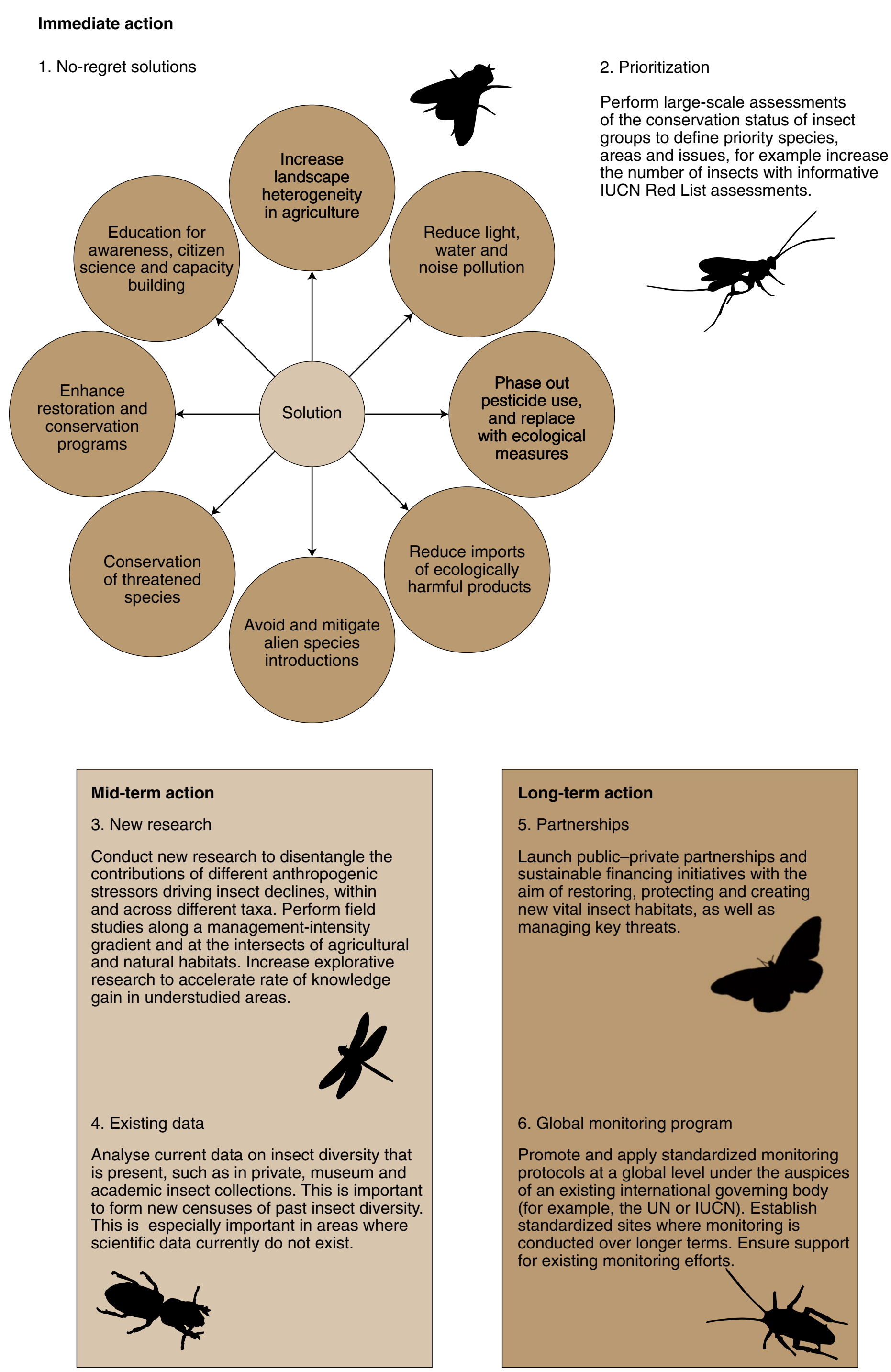

Fig. 1 | Roadmap to insect conservation and recovery, calling for action at short-, intermediate- and long-term timescales. No-regret measures for immediate utilization in insect conservation refer to actions that should be implemented as soon as possible. These solutions will be beneficial to society and biodiversity even if the direct effects on insects are not known as of yet (that is, no-regret solutions). This encompasses utilization of insect-friendly techniques that are effective, locally relevant and economically sound, for example, in farming, habitat management and urban development.

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Competing interests

The authors declare no competing interests.