COMMENTARY

Diversity of Insects in Nature protected Areas (DINA): an interdisciplinary German research project

Gerlind U. C. Lehmann[1,2] · Nikita Bakanov[3] · Martin Behnisch[4] ·
Sarah J. Bourlat[5] · Carsten A. Brühl[3] · Lisa Eichler[4] · Thomas Fickel[6,7] ·
Matthias F. Geiger[5] · Birgit Gemeinholzer[8] · Thomas Hörren[9] ·
Sebastian Köthe[1] · Alexandra Lux[6,7] · Gotthard Meinel[4] ·
Roland Mühlethaler[1] · Hanna Poglitsch[4] · Livia Schäffler[5] ·
Ulrich Schlechtriemen[10] · Florian D. Schneider[6,7] · Ralf Schulte[1] ·
Martin Sorg[9] · Maximilian Sprenger[10] · Stephanie J. Swenson[11] ·
Wiltrud Terlau[12] · Angela Turck[12] · Vera M. A. Zizka[5]

Abstract

Insect declines and biodiversity loss have attracted much attention in recent years, but lack of comprehensive data, conflicting interests among stakeholders and insufficient policy guidance hinder progress in preserving biodiversity. The project DINA (Diversity of Insects in Nature protected Areas) investigates insect communities in 21 nature reserves in Germany. All selected conservation sites border arable land, with agricultural practices assumed to influence insect populations. We taught citizen scientists how to manage Malaise traps for insect collection, and subsequently used a DNA metabarcoding approach for species identification. Vegetation surveys, plant metabarcoding as well as geospatial and ecotoxicological analyses will help to unravel contributing factors for the deterioration of insect communities. As a pioneering research project in this field, DINA includes a transdisciplinary dialogue involving relevant stakeholders such as local authorities, policymakers, and farmers, which aims at a shared understanding of conservation goals and action pathways. Stakeholder engagement combined with scientific results will support the development of sound policy recommendations to improve legal frameworks, landscape planning, land use, and conservation strategies. With this transdisciplinary approach, we aim to provide the background knowledge to implement policy strategies that will halt further decline of insects in German protected areas.

Communicated by Nigel E. Stork.

✉ Gerlind U. C. Lehmann
    gerlind.lehmann@nabu.de

Extended author information available on the last page of the article

Introduction

Insects are key organisms for terrestrial ecosystems and serious losses in insect diversity lead to a decline in insectivorous species, affect ecological functions like pollination and alter vegetation and community composition (IPBES 2019). An increasing number of publications show the gradual loss in insect species diversity, including biomass and abundance (summarized in Sánchez-Bayo and Wyckhuys 2019, 2021; van Klink et al. 2020; Wagner 2020). Most alarmingly, loss of insect biodiversity is not only observed on arable land but also within various types of nature conservation areas (Hallmann et al. 2017, 2021; Rada et al. 2019). An observed biomass reduction in insects of almost 80% over 27 years in German nature conservation areas (Hallman et al. 2017) has received widespread attention in the scientific community, the public and German policy makers (Bundestag 2017) and the authors called for a transdisciplinary approach analysing the current state of insect diversity.

The project DINA—Diversity of Insects in Nature protected Areas

The project (DINA 2021), developed by a consortium of eight partners, implements an interdisciplinary approach of comprehensive assessment of insect and associated plant diversity and pesticide exposure in combination with intensive stakeholder analyses and exchange in German nature protected areas. Combined with the scientific results, DINA aims for full integration into societal knowledge, as effective solutions can only be implemented through cooperation between stakeholders.

Sample sites were selected following geospatial analysis of all 8,836 nature protected areas with a total surface of around 15,843 km^2 (as of 2018). Based on GIS analysis, landscape indicators were evaluated and sites that fulfilled our requirements of grassland dominated habitat types with adjacent or integrated arable land, representing all German nature regions, were preselected. An initial analysis using the land cover model Germany LBM-DE 2018 (BKG 2018; Meinel and Reiter 2019) to identify the arable land shows how tightly these protected areas are interconnected with arable land: Germany's nature conservation areas contain around 450 km^2 of arable land inside their borders and arable land is in direct contact with nature conservation areas along a common borderline of 10,850 km, possibly affecting nature reserves and strictly protected habitats by range effects. If a buffer zone of 100 m around the sites is considered, the arable area increases to around 1,960 km2, or one eighth of the protected area itself (Meinel et al. unpubl. data). After the preselection process we evaluated the potential for cooperation of authorities and landowners, finally selecting 21 sites spread all over Germany (Fig. 1, Supplementary Table 1). This number still allows us to manage the incoming samples and is comprehensive enough to generate insights for other nature protected areas.

For insect bulk sampling Malaise traps are used, building upon the experience and recommendations of previous research (Sorg et al. 2019) for which first results have already been published, including insect biomass declines (Hallmann et al. 2017) and data on hoverflies (Diptera: Syrphidae, Hallmann et al. 2021). The Malaise trap is a well-established method for collecting flying insects (Ssymank et al. 2018; Skvarla et al. 2021) used in several projects worldwide such as the well-known Swedish Malaise trap project (Karlsson et al. 2020), the ILTER network across Europe (Mirtl et al. 2018), and recent and ongoing
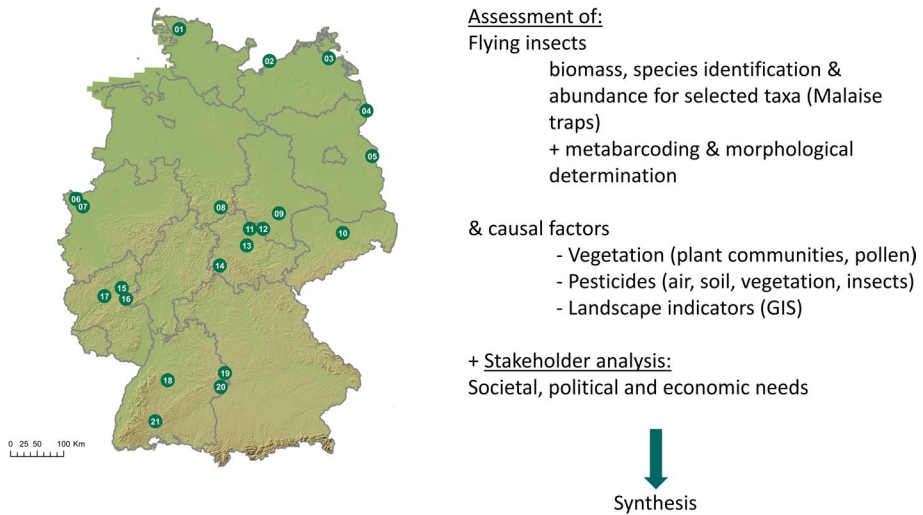
Assessment of:
Flying insects
        biomass, species identification &
        abundance for selected taxa (Malaise
        traps)
        + metabarcoding & morphological
        determination

& causal factors
       - Vegetation (plant communities, pollen)
       - Pesticides (air, soil, vegetation, insects)
       - Landscape indicators (GIS)

+ Stakeholder analysis:
Societal, political and economic needs

Synthesis

Fig. 1 Transdisciplinary approach in DINA and sampling sites across Germany

studies from Germany (Hardaluk et al. 2020; Hausmann et al. 2020; Welti et al. 2021). To allow data compatibility with previous studies (Hallmann et al. 2017, 2021), we use a standardized sampling design for Malaise traps and insect biodiversity assessment (Schwan et al. 1993; Ssymank et al. 2018). The advantage of Malaise traps over other methods is that they capture continuously, are semiquantitative and have low selectivity (overview in Ssymank et al. 2018). There are 33.466 estimated insect species in Germany (Klausnitzer 2003) of which more than 90 percent can fly. Therefore, Malaise traps cover the most species rich orders (such as Diptera), for which they are the recommended method (Brown 2021). Equally well represented in Malaise traps are the Hymenoptera (Prado et al. 2017; Ssymank et al. 2018) and Coleoptera (especially the small species) (Ulyshen et al. 2005), but ground dwelling and heavier insects may be underrepresented (Stork and Grimbacher 2006; Ssymank et al. 2018; Montgomery et al. 2021; Skvarla et al. 2021). Consequently, our approach comes close to an all-taxa biodiversity inventory (ATBI: Eymann et al. 2010) and represents the overall biodiversity better than studies of single insect orders, which dominate the research landscape (overviews in Sánchez-Bayo and Wyckhuys 2019, 2021). In addition, not only do we analyse caught insects, but also plant traces, to correlate insect activity with plant visitation and usage.

The traps operate continuously over the season, with a two-week collection interval, providing phenological data and the potential to detect species with short flying seasons. To reveal edge and geographical contour effects and to investigate whether the diversity of flying insects changes significantly along a gradient between the arable land and the nature reserve, we simultaneously positioned five traps along a transect 25 m apart (Fig. 2.). Transect sampling is useful for analysing heterogeneity within areas, and despite the long-established application for aquatic insects (e.g., Petersen et al. 2004) most Malaise trap designs are restricted to single traps per area (Sheikh et al. 2016). With this design, we can analyse insect biodiversity along the transects within and across sites, stratified for trap locality and correlated with geospatial parameters, vegetation parameters and pesticide residues (see Fig. 1). The spacing of 25 m between traps was chosen based on previous experience (Ssymank et al. 2018). Indeed, support comes
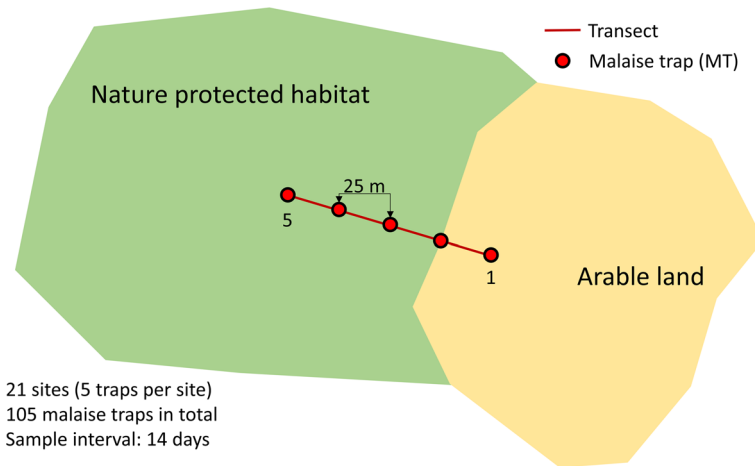
Fig. 2 Schematic illustration of our sampling design with a transect of traps reaching from arable land (MT1) into a nature protected habitat (MT2-5)

from recent experiments that found that species co-occurrence and biodiversity similarity decrease in Malaise traps further than 15 m apart (Steinke et al. 2020). The first trap was erected inside arable land, a second one directly at the border to a strictly protected habitat type (according to the EU habitats directive) and the other three further within the protected area (Fig. 2). With 21 areas and five traps per transect we deploy 105 traps in parallel, which is to our knowledge the largest number of Malaise traps in any past or ongoing program; for comparison Sweden was covered by 55 traps (Karlsson et al. 2020), and the LTER operates 79 traps in Germany (Welti et al. 2021). In total, our 105 traps with a two-week sampling interval sum up to around 1500 samples per year.

Our project goals were not limited to the scientific debate of insect declines, but to promote a transition towards a more sustainable nature protection policy. Citizen Science provides opportunities to engage people into ecological research (Silvertown 2009; MacPhail and Colla 2020; Sommerwerk et al. 2021), educate participants (Schleicher and Schmidt 2020) and enforce sustainability transitions (Sauermann et al. 2020). As the largest and oldest nature protection organization in Germany the Nature and Biodiversity Conservation Union (NABU) has recruited Citizen Scientists through its countrywide network. These volunteers are trained to manage the Malaise traps throughout the season, several also engage in pesticide sampling following protocols and video training. With our Citizen Science approach, we create regional support and the possibility to give people a sense of ownership of "their" nature protected area, and connect our research project with the larger community as an opportunity to democratize science (Alder et al. 2020).

In agreement with the standard protocol of the Entomological Society of Krefeld (Hallmann et al. 2017), all samples are weighed for biomass of the total insects. Total biomass represents the whole insect community (Shortall et al. 2009) and can be used as an indicator of ecosystem processes (Yang and Gratton 2014) and ecosystem function (Barnes et al. 2016). Despite its power as a bioindicator, especially for energy flow and impacts on higher trophic levels (Stepanian et al. 2020; Shaftel et al. 2021), biomass alone might not always be a reliable predictor of biodiversity (Vereecken et al. 2021).

DNA metabarcoding is used for taxonomic identification up to species level. This molecular approach is best suited for large-scale biodiversity assessments that would otherwise not be feasible with morphological identification methods due to time and cost constraints (Taberlet et al. 2012; Yu et al. 2012; Elbrecht et al. 2017). In contrast to single-specimen DNA barcoding based on Sanger sequencing, metabarcoding allows the analysis of bulk samples comprising hundreds of taxonomically diverse specimens through high throughput sequencing (Yu et al. 2012; Taberlet et al. 2012; reviewed in Liu et al. 2020). Hundreds of samples can be pooled and sequenced in one single run yielding millions of sequences, depending on the platform used. Through a specific indexing system and bioinformatic pipelines, sequences can subsequently be assigned back to their sample of origin, molecular units are defined, and the taxa contained in the sample are identified by comparison with DNA barcodes deposited in reference databases. DNA metabarcoding thus considerably up-scales diversity assessments of bulk samples, and accuracy is continuously improved through the refinement of molecular approaches and the expansion of reference libraries (BOLD, Ratnasingham and Hebert 2007; GBOL, Geiger et al. 2016a). Results from German Malaise trapping programs prove the strength of this approach for biodiversity assessments (Morinière et al. 2016; Geiger et al. 2016b; Hausmann et al. 2020; Hardulak et al. 2020).

However, amplification biases (Lamb et al. 2019; Krehenwinkel et al. 2017; Piñol et al. 2019) still prevent reliable estimates of species abundances using DNA metabarcoding. To compensate for this limitation, Diptera, Hymenoptera and Coleoptera from peak biomass samples will be morphologically identified and individuals counted. The combination of presence/ absence data for the entire range of species contained in bulk samples and species abundances for selected taxonomic groups will result in a hitherto unprecedented assessment of flying insect diversity in German protected areas. A key hypothesis is that intensive agriculture reduces insect diversity not only on farmland, but also affects populations in adjacent protected habitats via source-sink dynamics (Furrer and Pasinelli 2016).

The diversity and abundance of insect taxa in an area are highly dependent on available vegetation that provides structure and biological functions (Shinohara & Yoshida 2020). For this reason, an integral part of this project comprises vegetation surveys in the area surrounding the Malaise traps. To extend our understanding of the insects' local and temporal use of the surrounding vegetation, we will implement DNA metabarcoding of the plant traces found in the preservative ethanol of Malaise trap bottles. These traces represent pollen or plant fragments directly carried into the traps on the insect bodies or digested plant material expelled from the digestive tract. Although it will not be possible to directly link the insects with their particular plant species in this mixed sample approach, through information from the vegetation surveys and knowledge of the crops planted on the arable land, we will be able to determine whether insects in the protected areas travel to and from the arable land, thus increasing their exposure to pesticides.

Among other anthropogenic influencing factors, we investigate pesticide contamination in- and outside the nature protected areas. Because of the broad spectrum of toxicity of pesticides and their extensive use in agriculture, contamination of environmental matrices with pesticide residues from multiple applications is a critical issue (Brühl and Zaller 2019; IPBES IPBES). Only a few studies exist on terrestrial pesticide exposure in wildflowers (Botías et al 2015, 2017; David et a. 2016), agricultural soils (Hvězdová et al 2018; Silva et al. 2019) or entire landscapes (Humann-Guilleminot et al. 2019). Pesticide transport from cropping areas into adjacent non-target areas was measured in a playground in Southern Tyrol (Linhardt et al. 2019, 2021). By collecting environmental samples of soil and vegetation along a transect, we measure residue concentrations of

realistic current use pesticide mixtures and are able to evaluate contamination in central parts of nature conservation areas. Additionally, we also measure the pesticide residues on insects captured by the malaise traps. Passive movement of pesticides from cropping areas by wind can then be compared to active movement of insects, integrating pesticide use over a larger area around the conservation areas. These current use pesticide measurements are complemented by tree bark sampling to analyse aerial contaminants, including also legacy compounds, over a two-year time span.

To translate our research results into evidence-based cross-sectoral policy recommendations for an effective insect conservation in nature reserves, we correlate insect data with anthropogenic stressors. While different stakeholders in conservation and agriculture generally seem to agree on the finding of a nationwide insect decline, they may have fundamentally different opinions about the causes of biodiversity loss (Fickel et al. 2020). In general, gaps in knowledge and action prevent effective biodiversity protection (Mehring et al. 2017). Transdisciplinary approaches seek integration of stakeholders' knowledge into research to develop relevant and applicable recommendations for decision making at different scales from local to national and across stakeholder groups. Thus, within the framework of the stakeholder analysis, a semi-structured questionnaire as well as literature and media analysis and discourse field analysis are mainly used. Built on this, stakeholder knowledge is gathered via expert interviews and dialogue workshop series in the context of agricultural activities along nature protected areas. Due to this approach, research becomes valuable at local level and fosters knowledge transfer. With the inclusion of data of further nature protected areas, the data compiled up to that point will be supplemented by a subsequent quantitative survey on a much broader scale. This provides a solid basis for further dialogue and ensures the transferability of the results to other nature protected areas and neighbouring regions. Additionally, a national discussion forum between stakeholders from agriculture, administration, nature conservation, and science should vitalize networks among stakeholders, and between basic science and practical applications, and opens new management options for insect biodiversity conservation.

Expected results

The project DINA measures insect biodiversity at 21 representative nature protected areas in Germany. Results on insect diversity will include vegetation and spatial characteristics, correlated with agricultural practices in and around nature reserves, and risk assessment of pesticide exposure to evaluate possible drivers of biodiversity loss. Equally ambitious as the scientific endeavour, a societal exchange among stakeholders will be fostered, enabling mutual conflict resolution strategies to provide political and practical recommendations for evidence-based optimization of protected area planning and land use.

Compliance with ethical standards

References

Adler FR, Green AM, Sekercioglu CH (2020) Citizen science in ecology: a place for humans in nature. Ann NY Acad Sci 1469:52–64. https://doi.org/10.1111/nyas.14340

Barnes AD, Weigelt P, Jochum M, Ott D, Hodapp D, Haneda NF, Brose U (2016) Species richness and biomass explain spatial turnover in ecosystem functioning across tropical and temperate ecosystems. Philos Trans R Soc B 371:20150279

BKG (2018) Dokumentation – Digitales Landbedeckungsmodell für Deutschland LBM-DE2018. Bundesamt für Kartographie und Geodäsie

Botías C, David A, Horwood J, Abdul-Sada A, Nicholls E, Hill E, Goulson D (2015) Neonicotinoid residues in wildflowers, a potential route of chronic exposure for bees. Environ Sci Technol 49:12731–12740

Botías C, David A, Hill EM, Goulson D (2017) Quantifying exposure of wild bumblebees to mixtures of agrochemicals in agricultural and urban landscapes. Environ Pollut 222:73–82

Brown BV (2021) Sampling methods for adult flies (Diptera). In: Santos JC, Fernandes GW (eds) Measuring arthropod biodiversity. Springer, Cham. https://doi.org/10.1007/978-3-030-53226-0_7

Brühl CA, Zaller JG (2019) Biodiversity decline as a consequence of an inadequate environmental risk assessment of pesticides. Front Environm Sci 7:177

Bundestag (2017). Bundestagsdrucksache 18/12195 and 18/13142

David A, Botías C, Abdul-Sada A, Nicholls E, Rotheray EL, Hill EM, Goulson D (2016) Widespread contamination of wildflower and bee-collected pollen with complex mixtures of neonicotinoids and fungicides commonly applied to crops. Environ Intern 88:169–178

DINA (2021) Diversity of Insects in Nature protected Areas (DINA). www.dina-insektenforschung.de. Accessed 24 Jan 2021

Elbrecht V, Vamos EE, Meissner K, Aroviita J, Leese F (2017) Assessing strengths and weaknesses of DNA metabarcoding-based macroinvertebrate identification for routine stream monitoring. Methods Ecol Evol 8:1265–1275. https://doi.org/10.1111/2041-210X.12789

Eymann J, Degreef J, Häuser Ch, Monje JC, Samyn Y, van den Spiegel D (2010) Manual on field recording techniques and protocols for all Taxa Biodiversity Inventories and Monitoring. ABC Taxa 8:1–653

Fickel T, Lux A, Schneider FD (2020) Insektenschutz in agrarischen Kulturlandschaften Deutschlands. Eine Diskursfeldanalyse. ISOE-Materialien Soziale Ökologie 59. Frankfurt am Main: ISOE - Institut für sozial-ökologische Forschung

Furrer RD, Pasinelli G (2016) Empirical evidence for source-sink populations: a review on occurrence, assessments and implications. Biol Rev 91:782–795. https://doi.org/10.1111/brv.12195

Geiger MF, Astrin JJ, Borsch T, Burkhardt U, Grobe P, Hand R, Hausmann A, Hohberg K, Krogmann L, Lutz M, Monje C, Misof B, Morinière J, Müller K, Pietsch S, Quandt D, Rulik B, Scholler M, Traunspurger W, Haszprunar G, Wägele W (2016a) How to tackle the molecular species inventory for an industrialized nation-lessons from the first phase of the German Barcode of Life initiative GBOL (2012–2015). Genome 59:661–670. https://doi.org/10.1139/gen-2015-0185

Geiger MF, Moriniere J, Hausmann A, Haszprunar G, Wägele W, Hebert PD, Rulik B (2016) Testing the Global Malaise Trap Program—How well does the current barcode reference library identify flying insects in Germany? Biodivers Data J 1(4):e10671. https://doi.org/10.3897/BDJ.4.e10671

Hallmann CA, Sorg M, Jongejans E, Siepel H, Hofland N, Schwan H, Stenmans W, Müller A, Sumser H, Hörren T, Goulson D, de Kroon H (2017) More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PLoS ONE 12:e0185809

Hallmann CA, Ssymank A, Sorg M, de Kroon H, Jongejans E (2021) Insect biomass decline scaled to species diversity: general patterns derived from a hoverfly community. Proc Natl Acad Sci USA 118:e2002554117. https://doi.org/10.1073/pnas.2002554117

Hardulak LA, Morinière J, Hausmann A, Hendrich L, Schmidt S, Doczkal D, Müller J, Hebert PDN, Haszprunar G (2020) DNA metabarcoding for biodiversity monitoring in a national park: screening for invasive and pest species. Mol Ecol Resour 20:1542–1557

Hausmann A, Segerer AH, Greifenstein T, Knubben J, Morinière J, Bozicevic V, Doczkal D, Günter A, Ulrich W, Habel JC (2020) Toward a standardized quantitative and qualitative insect monitoring scheme. Ecol Evol 10:4009–4020

Humann-Guilleminot S, Binkowski ŁJ, Jenni L, Hilke G, Glauser G, Helfenstein F (2019) A nation-wide survey of neonicotinoid insecticides in agricultural land with implications for agri-environment schemes. J Appl Ecol 56:1502–1514

Hvězdová M, Kosubová P, Košíková M, Scherr KE, Šimek Z, Brodský L, Šudoma M, Škulcová L, Sáňka M, Svobodová M, Krkošková L, Vašíčková J, Neuwirthová N, Bielská L, Hofman J (2018) Currently and recently used pesticides in Central European arable soils. Sci Total Environ 613–614:361–370. https://doi.org/10.1016/j.scitotenv.2017.09.049

IPBES (2019) Global Assessment Report on Biodiversity and Ecosystem Services. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Brondizio ES, Settele J, Díaz S, Ngo HT (eds) IPBES Secretariat, Bonn, Germany

Karlsson D, Hartop E, Forshage M, Jaschhof M, Ronquist F (2020) The Swedish Malaise trap project: a 15 year retrospective on a countrywide insect inventory. Biodiv Data J 8:e47255. https://doi.org/10.3897/BDJ.8.e47255

Klausnitzer B (2003) Gesamtübersicht zur Insektenfauna Deutschlands. Entomol Nachr Ber 47:57–66

Krehenwinkel H, Wolf M, Lim JY, Rominger AJ, Simison WB, Gillespie RG (2017) Estimating and mitigating amplification bias in qualitative and quantitative arthropod metabarcoding. Sci Rep 7:17668. https://doi.org/10.1038/s41598-017-17333-x

Lamb PD, Hunter E, Pinnegar JK, Creer S, Davies RG, Taylor MI (2019) How quantitative is metabarcoding: a meta-analytical approach. Mol Ecol 28:420–430

Linhart C, Niedrist GH, Nagler M, Nagrani R, Temml V, Bardelli T, Wilhalm T, Riedl A, Zaller JG, Clausing P, Hertoge K (2019) Pesticide contamination and associated risk factors at public playgrounds near intensively managed apple and wine orchards. Environ Sci Eur 31:28

Linhart C, Panzacchi S, Belpoggi F, Clausing P, Zaller JG, Hertoge K (2021) Year-round pesticide contamination of public sites near intensively managed agricultural areas in South Tyrol. Environ Sci Eur 33:1–12

Liu M, Clarke LJ, Baker SC, Jordan GJ, Burridge CP (2020) A practical guide to DNA metabarcoding for entomological ecologists. Ecol Entomol 45:373–385. https://doi.org/10.1111/een.12831

MacPhail VJ, Colla SR (2020) Power of the people: a review of citizen science programs for conservation. Biol Conserv 249:108739. https://doi.org/10.1016/j.biocon.2020.108739

Meinel G, Reiter D (2019) Nutzung des Landbedeckungsmodells LBM-DE für das Flächenmonitoring – Bewertung und Ergebnisse. In: Meinel G, Schumacher U, Behnisch M, Krüger T (eds): Flächennutzungsmonitoring XI. Flächenmanagement – Bodenversiegelung – Stadtgrün. IÖR Schriften 77:169–179.

Mehring M, Bernard B, Hummel D, Liehr S, Lux A (2017) Halting biodiversity loss: how social-ecological biodiversity research makes a difference. Int J Biodivers Sci Ecosyst Serv Manag 13:172–180. https://doi.org/10.1080/21513732.2017.1289246

Mirtl M, Borer T, Djukic I, Forsius M, Haubold H, Hugo W, Jourdan J, Lindenmayer D, McDowell WH, Muraoka H, Orenstein DE, Pauw JC, Peterseil J, Shibata H, Wohner C, Yu X, Haase P (2018) Genesis, goals and achievements of Long-Term Ecological Research at the global scale: a critical review of ILTER and future directions. Sci Total Environ 626:1439–1462

Montgomery GA, Belitz MW, Guralnick RP, Tingley MW (2021) Standards and best practices for monitoring and benchmarking insects. Front Ecol Evol 8:513

Morinière J, Cancian de Araujo B, Lam AW, Hausmann A, Balke M, Schmidt S, Hendrich L, Doczkal D, Fartmann B, Arvidsson S, Haszprunar G (2016) Species Identification in Malaise Trap samples by DNA barcoding based on NGS technologies and a scoring matrix. PLoS ONE 11:e0155497. https://doi.org/10.1371/journal.pone.0155497

Petersen I, Masters Z, Hildrew AG, Ormerod SJ (2004) Dispersal of adult aquatic insects in catchments of differing land use. J Appl Ecol 41:934–950

Piñol J, Senar MA, Symondson WOC (2019) The choice of universal primers and the characteristics of the species mixture determine when DNA metabarcoding can be quantitative. Mol Ecol 28:407–419. https://doi.org/10.1111/mec.14776

Prado SG, Ngo HT, Florez JA, Collazo JA (2017) Sampling bees in tropical forests and agroecosystems: a review. J Insect Conserv 21:753–770. https://doi.org/10.1007/s10841-017-0018-8

Rada S, Schweiger O, Harpke A, Kühn E, Kuras T, Settele J, Musche M (2019) Protected areas do not mitigate biodiversity declines: a casestudy on butterflies. Divers Distrib 25:217–224. https://doi.org/10.1111/ddi.12854

Ratnasingham S, Hebert PDN (2007) BARCODING: bold: The Barcode of Life Data System (http://www.barcodinglife.org). Mol Ecol Notes 7:355–364. https://doi.org/10.1111/j.1471-8286.2007.01678.x

Sánchez-Bayo F, Wyckhuys KAG (2019) Worldwide decline of the entomofauna: A review of its drivers. Biol Conserv 232:8–27. https://doi.org/10.1016/j.biocon.2019.01.020

Sánchez-Bayo F, Wyckhuys KAG (2021) Further evidence for a global decline of the entomofauna. Austral Entomol 60:9–26. https://doi.org/10.1111/aen.12509

Sauermann H, Vohland K, Antoniou V, Balázs B, Göbel C, Karatzas K et al (2020) Citizen science and sustainability transitions. Res Policy 49:103978

Schleicher K, Schmidt C (2020) Citizen science in Germany as research and sustainability education: analysis of the main forms and foci and its relation to the sustainable development goals. Sustainability 12:6044. https://doi.org/10.3390/su12156044

Schwan H, Sorg M, Stenmans W (1993) Naturkundliche Untersuchungen zum Naturschutzgebiet "Die Spey" (Stadt Krefeld, Kreis Neuss) – I. Untersuchungsstandorte und Methoden. Nat Niederrhein (NF) 8:1–13

Shaftel R, Rinella DJ, Kwon E, Brown SC, Gates HR, Kendall S, Lank DB, Liebezeit JR, Payer DC, Rausch J, Saalfeld ST, Sandercock BK, Smith PA, Ward DH, Lanctot RB (2021) Predictors of invertebrate biomass and rate of advancement of invertebrate phenology across eight sites in the North American Arctic. Polar Biol 44:237–257

Sheikh AH, Thomas M, Bhandari R, Meshram H (2016) Malaise trap and insect sampling: Mini Review. Bio Bull 2:35–40

Shinohara N, Yoshida T (2021) Why species richness of plants and herbivorous insects do or do not correlate. Ecol Res 36:258–265. https://doi.org/10.1111/1440-1703.12189

Shortall CR, Moore A, Smith E, Hall MJ, Woiwod IP, Harrington R (2009) Long-term changes in the abundance of flying insects. Insect Conserv Divers 2:251–260

Silva V, Mol HG, Zomer P, Tienstra M, Ritsema CJ, Geissen V (2019) Pesticide residues in European agricultural soils—a hidden reality unfolded. Sci Total Environ 653:1532–1545

Silvertown J (2009) A new dawn for citizen science. Trends Ecol Evol 24:467–471

Skvarla MJ, Larson JL, Fisher JR, Dowling AP (2021) A review of terrestrial and Canopy Malaise Traps. Ann Entomol Soc Am 114:27–47

Sommerwerk N, Geschke J, Schliep R, Esser J, Glöckler F, Grossart H-P, Hand R, Kiefer S, Kimmig S, Koch A, Kühn E, Larondelle N, Lehmann G, Munzinger S, Rödl T, Werner D, Wessel M, Vohland K (2021) Vernetzung und Kooperation ehrenamtlicher und akademischer Forschung im Rahmen des nationalen Biodiversitätsmonitorings—Herausforderungen und Lösungsstrategien. Natur Landschaft, in press

Sorg M, Ssymank A, Hörren T (2019) Bestandsrückgänge von Insekten in Schutzgebieten – bisherige Erkenntnisse aus einem laufenden Forschungsprogramm. Natur Landschaft 96:255–260. https://doi.org/10.17433/6.2019.50153701.255-260

Ssymank A, Sorg M, Doczkal D, Rulik B, Merkel-Wallner G, Vischer-Leopold M (2018) Praktische Hinweise und Empfehlungen zur Anwendung von Malaisefallen für Insekten in der Biodiversitätserfassung und im Monitoring. Ser Nat 1:1–12

Steinke D, Braukmann TW, Manerus L, Woodhouse A, Elbrecht V (2020) Effects of Malaise trap spacing on species richness and composition of terrestrial arthropod bulk samples. bioRxiv 2020.09.30.321430. https://doi.org/10.1101/2020.09.30.321430

Stepanian PM, Entrekin SA, Wainwright CE, Mirkovic D, Tank JL, Kelly JF (2020) Declines in an abundant aquatic insect, the burrowing mayfly, across major North American waterways. Proc Natl Acad Sci USA 117:2987–2992

Stork NE, Grimbacher PS (2006) Beetle assemblages from an Australian tropical rainforest show that the canopy and the ground strata contribute equally to biodiversity. Proc R Soc B 273:1969–1975

Taberlet P, Coissac E, Pompanon F, Brochmann C, Willerslev E (2012) Towards next-generation biodiversity assessment using DNA metabarcoding. Mol Ecol 21:2045–2050. https://doi.org/10.1111/j.1365-294X.2012.05470.x

Ulyshen MD, Hanula JL, Horn S (2005) using Malaise traps to sample ground beetles (Coleoptera: Carabidae). Can Entomol 137:251–256

van Klink R, Bowler DE, Gongalsky KB, Swengel AB, Gentile A, Chase JM (2020) Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances. Science 368:417–420. https://doi.org/10.1126/science.aax9931

Vereecken NJ, Weekers T, Leclercq N, De Greef S, Hainaut H, Molenberg JM, Martin Y, Janssens X, Nöel G, Pauly A, Roberts SPM, Marshall L (2021) Insect biomass is not a consistent proxy for biodiversity metrics in wild bees. Ecol Indic 121:107132

Wagner DL (2020) Insect declines in the Anthropocene. Annu Rev Entomol 65:457–480

Welti EA, Zajicek P, Ayasse M, Bornholdt T, Buse J, Dziock F, Engelmann RA, Englmeier J, Fellendorf M, Förschler MI, Frenzel M, Fricke U, Ganuza C, Hippke M, Hoenselaar G, Kaus-Thiel A, Mandery K, Marten A, Monaghan MT, Morkel C, Müller J, Puffpaff S, Redlich S, Richter R, Rojas Botero S, Scharnweber T, Scheiffarth G, Schmidt Yáñez P, Schumann R, Seibold S, Steffan-Dewenter I, Stoll S, Tobisch C, Twietmeyer S, Uhler J, Vogt J, Weis D, Weisser WW, Wilmking M, Haase P (2021) Climate, latitude, and land cover predict flying insect biomass across a German malaise trap network. Preprint from bioRxiv, 03 Feb 2021. https://doi.org/10.1101/2021.02.02.429363

Yang LH, Gratton C (2014) Insects as drivers of ecosystem processes. Curr Opin Insect Sci 2:26–32

Yu DW, Ji YQ, Emerson BC, Wang XY, Ye CX, Yang CY, Ding ZL (2012) Biodiversity soup: metabarcoding of arthropods for rapid biodiversity assessment and biomonitoring. Methods Ecol Evol 3:613–623

Authors and Affiliations

Gerlind U. C. Lehmann[1,2] · **Nikita Bakanov**[3] · **Martin Behnisch**[4] · **Sarah J. Bourlat**[5] · **Carsten A. Brühl**[3] · **Lisa Eichler**[4] · **Thomas Fickel**[6,7] · **Matthias F. Geiger**[5] · **Birgit Gemeinholzer**[8] · **Thomas Hörren**[9] · **Sebastian Köthe**[1] · **Alexandra Lux**[6,7] · **Gotthard Meinel**[4] · **Roland Mühlethaler**[1] · **Hanna Poglitsch**[4] · **Livia Schäffler**[5] · **Ulrich Schlechtriemen**[10] · **Florian D. Schneider**[6,7] · **Ralf Schulte**[1] · **Martin Sorg**[9] · **Maximilian Sprenger**[10] · **Stephanie J. Swenson**[11] · **Wiltrud Terlau**[12] · **Angela Turck**[12] · **Vera M. A. Zizka**[5]

[1] Nature and Biodiversity Conservation Union (NABU), Charitéstraße 3, 10117 Berlin, Germany

[2] Evolutionary Ecology, Humboldt University Berlin, Invalidenstrasse 110, 10115 Berlin, Germany

[3] Institute for Environmental Sciences Landau, University Koblenz Landau, Fortstraße 7, 76829 Landau, Germany

[4] Leibniz Institute of Ecological Urban and Regional Development (IOER), Dresden, Germany

[5] Zoological Research Museum Alexander Koenig – Leibniz Institute for Animal Biodiversity (ZFMK), Adenauerallee 160, 53113 Bonn, Germany

[6] Institute for Social-Ecological Research (ISOE), Hamburger Allee 45, 60486 Frankfurt am Main, Germany

[7] Senckenberg Biodiversity and Climate Research Centre, Senckenberganlage 32, 60325 Frankfurt am Main, Germany

[8] University Kassel, Heinrich-Plett-Strasse 40, 34132 Kassel, Germany

[9] Entomological Society Krefeld (EVK), Marktstraße 159, 47798 Krefeld, Germany

[10] Integrated Environmental Monitoring (TIEM), Hohenzollernstraße 20, 44135 Dortmund, Germany

[11] Justus Liebig University, Heinrich-Buff-Ring 38, 35392 Giessen, Germany

[12] International Centre for Sustainable Development (IZNE), University of Applied Sciences Bonn-Rhein-Sieg, Grantham-Allee 20, 53757 Sankt Augustin, Germany