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OPINION PAPER

Improving wild bee monitoring, sampling methods, and conservation

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ABSTRACT

Bees are the most important group of insect pollinators, but their populations are declining. To gain a better understanding of wild bee responses to different stressors (e.g. land-use change) and conservation measures, regional and national monitoring schemes are currently being established in Germany, which is used here as a model region, and in many other countries. We offer perspectives on how to best design future bee monitoring programs with a focus on evaluating the implementation of conservation measures. We discuss different traditional and novel sampling methods, their efficacy depending on research questions and the life-history traits of target species, and how greater standardization of wild bee sampling and monitoring methods can make data more comparable, contributing to the identification of general trends and mechanisms driving bee populations. Furthermore, the potential impact of bee sampling itself on bee populations is discussed.

Introduction

Pollinators are essential for the reproduction of 88% of flowering wild plants (Ollerton et al., 2011) and can increase production of 75% of the world's economically most important crops (Klein et al., 2007). Bees are a key group of insect pollinators (Corbet et al., 1991; Goulson et al., 2015). However, wild bee populations are declining, especially in intensively managed agricultural landscapes, due to multiple, potentially interacting stressors (Dicks et al., 2021; Goulson et al., 2015; Potts et al., 2016; Powney et al., 2019). To better understand how wild bee and other insect populations are developing in space and over time, and how they respond to different stressors (e.g. land-use change, climate change) but also to conservation measures, national and regional monitoring schemes are currently being established (Breeze et al., 2021; Halvorson et al., 2021), for example in the EU (Potts et al., 2021) or the federal state of Baden-Württemberg in Germany (Bittner et al., 2020).

The need for monitoring to assess biodiversity changes has become apparent since national and international conservation targets were set for example by the Convention on Biological Diversity, the Sustainable Development goals in the UN 2030 Agenda or the International Platform on Biodiversity and Ecosystem Services, to be able to evaluate developments toward these targets (Assembly & Committee, 2003; Cf,

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2015; Harrop, 2011; Larigauderie & Mooney, 2010). Monitoring schemes are designed to determine the status of biological diversity and to assess changes over space and time by continuously revisiting sites, and can be used to identify effects of management (Goldsmith, 2012; Pollard et al., 1994). Prior to these systematic and concerted efforts, most knowledge on species populations has been generated without monitoring in mind, but can now serve as valuable benchmarks allowing comparisons over longer time periods.

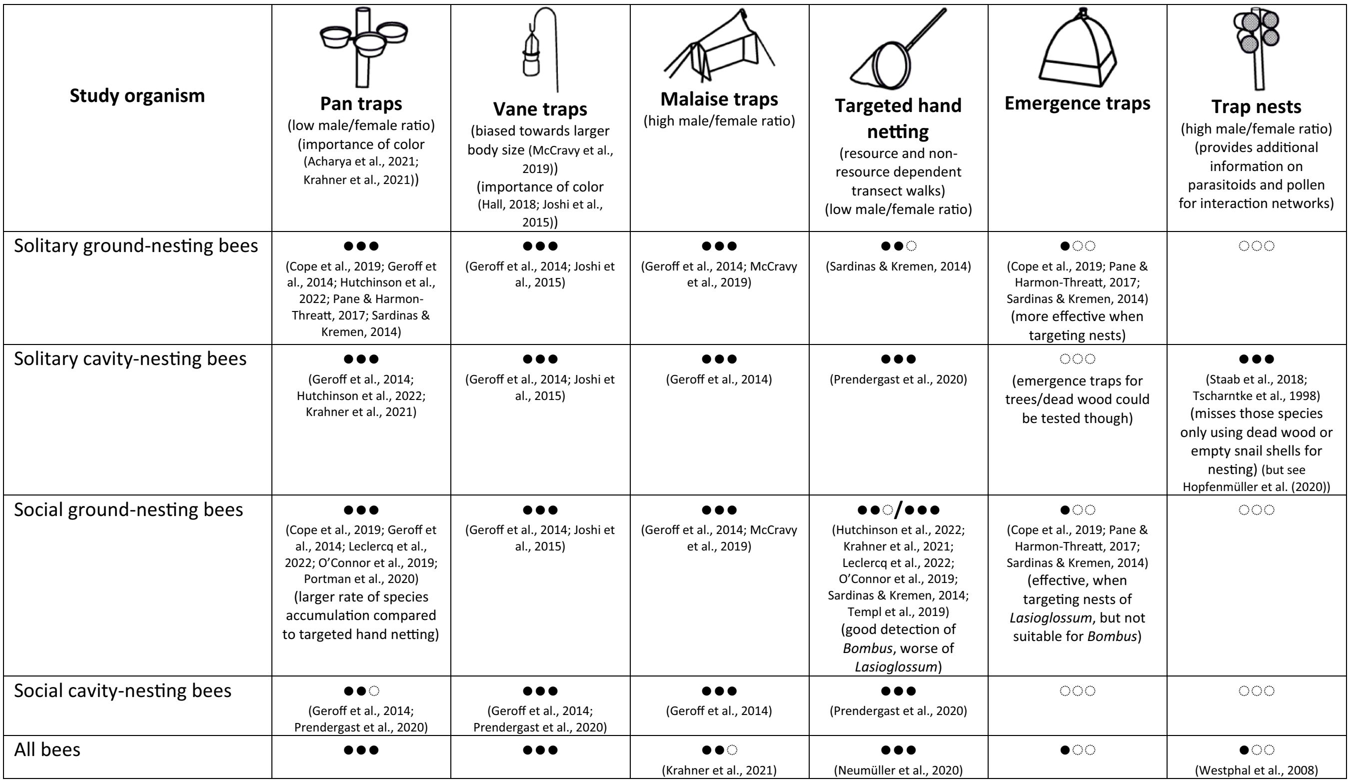
For the ongoing development of bee monitoring schemes, using Germany as an example, we provide an overview of different bee sampling methods and their suitability to sample bees with different traits. We discuss perspectives on how to best design such monitoring schemes, with a focus on their potential to evaluate conservation measures such as the restoration of flowering habitats (see Box 1 for a definition of the terms “sampling” and “monitoring”).

Sampling data derived from, for example, monitoring schemes, and citizen science data on bee populations and their distributions harbor great potential to inform on the causes of bee declines, but also on the potential reversal of negative trends after the implementation of targeted conservation or habitat restoration measures (Cole et al., 2020; Kühl et al., 2020; Sutter et al., 2017; Watson et al., 2019). When gathered, combined, evaluated and analyzed, for example in meta-analyses and reviews, these data can be upscaled to inform on the state of bee populations in different regions and habitats and may enable the identification of mechanisms driving bee population dynamics. However, different sampling methods (see Fig. 1) and sampling designs (e.g. timing and duration of sampling events) are typically used to monitor or sample bees, resulting in data from different monitoring schemes or other bee sampling data often not being comparable (Montgomery et al., 2021; Woodard et al., 2020). Here, we aim to contribute to the development of more standardized, harmonized methods and guidelines for future studies sampling and monitoring wild bees. Different wild bee sampling methods are more or less suitable, depending on research questions and the life-history traits of the bee sub-groups targeted (Krahner et al., 2021; Prendergast et al., 2020; Thompson et al., 2021). We discuss different traditional and novel wild bee sampling methods and their efficacies depending on traits of target species, as well as potential impacts of lethal sampling on bee populations.

Furthermore, we discuss the potential of monitoring schemes to detect responses of bees to conservation measures, to track and evaluate their impact and success. The effects of conservation measures on local bee populations can differ, depending on local and landscape factors (Schubert et al., 2022; Warzecha et al., 2021). When these influential factors are taken into account, and conservation measures have clear and measurable targets, data from monitoring schemes can help to evaluate them and inform decision making regarding the type and placement of such measures in the landscape.

Suitable sampling methods depend on research questions and study system

To make studies and datasets comparable and hence more suitable for meta-analyses, researchers need standardized sampling methods for future studies and monitoring schemes, to be able to gain more general insights into species-environment relationships (Espín et al., 2016). Wild bees are highly variable with regard to their life histories, physiological and functional traits, thus, requiring different sampling methods depending on the bee sub-groups targeted and their respective traits (Krahner et al., 2021; Prendergast et al., 2020; Thompson et al., 2021). For example, in Germany alone, there are more than 560 species of wild bees reaching from solitary mason bees (*Osmia* spp.) to eusocial bumble bees (*Bombus* spp.), from tiny sweat bees (*Nomioides minutissimus*, 4-5 mm) to large carpenter bees (*Xylocopa violacea*, 20-30 mm), either



Study organism	**Pan traps** (low male/female ratio) (importance of color (Acharya et al., 2021; Krahner et al., 2021))	**Vane traps** (biased towards larger body size (McCravy et al., 2019)) (importance of color (Hall, 2018; Joshi et al., 2015))	**Malaise traps** (high male/female ratio)	**Targeted hand netting** (resource and non-resource dependent transect walks) (low male/female ratio)	**Emergence traps**	**Trap nests** (high male/female ratio) (provides additional information on parasitoids and pollen for interaction networks)
Solitary ground-nesting bees	●●● (Cope et al., 2019; Geroff et al., 2014; Hutchinson et al., 2022; Pane & Harmon-Threatt, 2017; Sardinas & Kremen, 2014)	●●● (Geroff et al., 2014; Joshi et al., 2015)	●●● (Geroff et al., 2014; McCravy et al., 2019)	●●○ (Sardinas & Kremen, 2014)	●○○ (Cope et al., 2019; Pane & Harmon-Threatt, 2017; Sardinas & Kremen, 2014) (more effective when targeting nests)	○○○
Solitary cavity-nesting bees	●●● (Geroff et al., 2014; Hutchinson et al., 2022; Krahner et al., 2021)	●●● (Geroff et al., 2014; Joshi et al., 2015)	●●● (Geroff et al., 2014)	●●● (Prendergast et al., 2020)	○○○ (emergence traps for trees/dead wood could be tested though)	●●● (Staab et al., 2018; Tscharntke et al., 1998) (misses those species only using dead wood or empty snail shells for nesting) (but see Hopfenmüller et al. (2020))
Social ground-nesting bees	●●● (Cope et al., 2019; Geroff et al., 2014; Leclercq et al., 2022; O’Connor et al., 2019; Portman et al., 2020) (larger rate of species accumulation compared to targeted hand netting)	●●● (Geroff et al., 2014; Joshi et al., 2015)	●●● (Geroff et al., 2014; McCravy et al., 2019)	●●○/●●● (Hutchinson et al., 2022; Krahner et al., 2021; Leclercq et al., 2022; O’Connor et al., 2019; Sardinas & Kremen, 2014; Templ et al., 2019) (good detection of *Bombus*, worse of *Lasioglossum*)	●○○ (Cope et al., 2019; Pane & Harmon-Threatt, 2017; Sardinas & Kremen, 2014) (effective, when targeting nests of *Lasioglossum*, but not suitable for *Bombus*)	○○○
Social cavity-nesting bees	●●○ (Geroff et al., 2014; Prendergast et al., 2020)	●●● (Geroff et al., 2014; Prendergast et al., 2020)	●●● (Geroff et al., 2014)	●●● (Prendergast et al., 2020)	○○○	○○○
All bees	●●●	●●●	●●○ (Krahner et al., 2021)	●●● (Neumüller et al., 2020)	●○○	●○○ (Westphal et al., 2008)

Fig. 1. Suitability of different sampling methods for solitary/social bee species nesting in the ground/in cavities. Honey bees (*Apis mellifera*) were included as “social cavity-nesting bees”. Cleptoparasitic bees can usually be sampled in the same way as their hosts. The performance of sampling methods are indicated: from ●●● (most suitable, community of bees well represented in trap type) to ○○○ (least suitable, community of bees not well represented in trap type). Performance ratings are based on the references listed and the expert opinions of the authors.

Box 1
Definitions of the terms “sampling” and “monitoring” as used in this paper

Sampling: Counting bees with observations and/or trapping. Sampling data can be used to answer ecological questions, or, when sampling is done repeatedly over time, can be used for monitoring.

Monitoring: Repeated sampling of bees to track changes of bee communities/populations over time (multiple years). Monitoring schemes can have sophisticated designs and often include experimental approaches. Bee monitoring can be used to compare changes over time across habitats, regions, or in response to local changes, such as the implementation of conservation measures.

nesting below- or above-ground, or parasitizing other wild bee species (e.g. *Coelioxys* spp. or *Nomada* spp.) (Westrich, 2019). The most suitable sampling methods depend on the research questions, or, for monitoring schemes, on the type of indicator used and the bee groups or traits of interest. Below, we provide an overview of methods widely used to sample wild bees, including examples of their suitability with regard to target species. Given there always is a trade-off between comprehensiveness and, for example, costs, time and labor, it is important to clearly formulate the research question or indication, in order to find the best compromise between comprehensiveness and feasibility. Aspects of the studied system, such as accessibility as well as spatial and temporal extent and heterogeneity, may further influence the suitability of methods (Prado et al., 2017).

Suitable methods for sampling different groups of wild bees

Suitable methods for sampling wild bees can be chosen based on the functional traits shared by the target species and/or community of interest (Thompson et al., 2021). Here, as an example, we differentiate among bee species based on nesting substrate and sociality. These two traits were chosen, because there is literature available comparing the suitability of sampling methods, and because it is a fitting example to show contrasting suitability of methods depending on species groups. Fig. 1 provides an overview of methods suitable for sampling bees in the respective categories, and also shows how methods can differ in their suitability depending on the target bee group or species. These differences require caution when extrapolating results obtained with a specific sampling method to species with different life history traits or even across bee communities. An additional functional trait of interest is how narrow and specialized the preference of a species is regarding food sources. To sample oligolectic (specialized) bee species (for example *Osmia rapunculi* oligolectic on Campanulaceae), targeted hand netting at known food-plants is the most suitable sampling method (Larsson & Franzen, 2008). Other traits of importance not discussed here are, for example, body size, parasitism, or rareness. For more details on different sampling approaches, we refer to the sources provided in Fig. 1.

Many studies suggest a combination of pan traps and hand netting as most efficient in sampling the entire bee community, taking into account funding limitations, available scientific expertise and staff (European Commission, Joint Research Centre, 2021; Krahner et al., 2021; Montgomery et al., 2021; Schindler et al., 2013; Templ et al., 2019; Westphal et al., 2008). Recently, those sampling methods that are lethal and relatively unspecific have been criticized for killing bees and non-target species unnecessarily (Drinkwater et al., 2019). The impact of sampling on bee populations compared to other anthropogenic and natural factors, and measures to limit lethal sampling are discussed in Box 2.

Scales to be considered for monitoring

Different scales are to be considered, when designing schemes for monitoring bee populations: The spatial scale to measure variation within and between landscapes, and the temporal scale to account for within (community changes) and between (population dynamics) year variation.

To determine sampling locations, sampling sites are to be chosen at the landscape scale. In general, wild bees forage within 1 km of their nest (except for large or social species) (Kendall et al., 2022). Sampling locations should therefore be at least 1-2 km apart, for them to be spatially independent. The local scale is to be considered for the determination of sampling points within these sampling sites. To make best use of synergies between gathered data and data from pre-existing monitoring schemes, researchers should aim for maximal harmonization of sampling regimes. For example, the EU pollinator monitoring scheme (EU-PoMS) proposes the Land Use and Coverage Area frame Survey (LUCAS) sample grid as the basis for choosing sampling sites, because of a low bias with regard to specific regions, habitats or recorder locations, and the availability of additional data from other monitoring projects (e.g. on soil) (Orgiazzi et al., 2018; Potts et al., 2021). To achieve a good representation of different habitat types, which is especially important in heterogeneous landscapes, sampling point distribution within sampling sites has been suggested to be based on a stratified-random basis (Scherber et al., 2019).

In addition to the spatial scale, monitoring programs need to consider the appropriate temporal resolution of sampling events. One straight-forward approach to address this aspect is to sample continuously over the entire bee season. However, while in theory, this approach is feasible for all trap methods, the limited availability of resources will often necessitate discontinuous sampling intervals (Potts et al., 2021). Timing of sampling events is then pivotal, due to temporal species turnover in bee communities, and (when monitoring abundances) due to seasonal fluctuations in bee populations, e.g. in social bee species (Duelli et al., 1999). When monitoring larger regions, it becomes increasingly important to adjust the timing of sampling events to the phenology of the bee community. In practice, this can be achieved by linking bee sampling events to plant phenological indicators, such as the onset of flowering of a widespread plant species (Cane, 2021; Duelli et al., 1999). In this way, and irrespective of the extent of the monitoring area, inter-annual variations in phenology will be accounted for, making it more likely to detect relevant changes in the monitored metric.

Additionally, long-term feasibility is a pivotal aspect of a monitoring scheme. In addition to staff and material costs, this also entails legal aspects. In some countries, permissions need to be granted by authorities to any person sampling bees. In the Federal Republic of Germany, for example, this means a considerable amount of time has to be spent for applying for permissions with multiple authorities, depending on the states covered in the monitoring. To minimize time and effort spent and to ensure long-term feasibility from a legal perspective, the applicant should therefore attempt to obtain a long-term validity of the permits.

Current and future wild bee sampling and monitoring in Germany and beyond

In Germany, there are several regional and national monitoring schemes for insects, including bees, currently being developed and implemented. While some types of landscape are already in focus, such as the agricultural landscape (BienABest, MonViA), conservation areas

(DINA) or both (Bundesweites Insektenmonitoring, Insektenmonitoring Baden-Württemberg), as well as urban habitats (Bienenstadt Braunschweig (Weber et al., 2023), red list of wild bees and wasps in Hamburg) (see Appendix A: Table 1 for details), other habitats such as forest (margins) are not yet monitored extensively (but see Zacharias et al. (2011)). In the past, sampling of insects has mostly been done as part of short-term projects. Revisiting sites is, however, essential for tracking long-term changes in bee abundance and community composition. Recurrent sampling of the same locations should, therefore, be part of every monitoring scheme. Moreover, site selection could be based on sampling locations from the past to expand and build upon data that were collected decades or centuries ago, enabling the analysis of long-term dynamics. It should be considered though, that selection of historically sampled sites has likely been biased and may not be representative (Fournier et al., 2019).

To render generated data more comparable and to gain insights into changes in populations of bee species across scales, synergies could be created through additional collaboration, coordination, and networking across the various monitoring schemes and bee sampling studies and projects. For example, making data open access according to FAIR principles and using common databases such as GBIF (Global Biodiversity Information Facility, https://www.gbif.org/) would enable not only streamlining IT-infrastructure but also facilitate simple and long-term access to data and thus its use for comparisons and meta-analyses. For Europe, GBIF contains occurrence records for more than 3,500,000 individuals from 1627 (of around 2000) species of bees (as of February 2023), and has been used to analyze global patterns of bee species richness (Nieto et al., 2017; Zattara & Aizen, 2021). In Germany, the need to link different monitoring schemes has recently been acknowledged resulting in the foundation of the National Monitoring Centre for Biodiversity, a national institution solely dedicated to this purpose (https://www.monitoringzentrum.de/en).

There have also been calls to limit sampling to match identification capacities, so that all individuals are identified, to avoid accumulating unused data when proper long-term storage cannot be guaranteed, and to focus targeted sampling efforts on areas with accurate historic records addressing specific hypotheses regarding conservation management (Portman et al., 2020; Tepedino & Portman, 2021). Enhanced collaboration, communication, and information exchange could help to prevent redundant sampling, e.g. by unnecessarily sampling the same community or region. In this regard, it should also be considered that non-target organisms caught in traps (so called "by-catch") may contain valuable information for other monitoring schemes or working groups (Hribar, 2020; Spears & Ramirez, 2015).

Options to fill data gaps using citizen science and other non-academic sources

Citizen scientists provide a large source of data which could contribute to wild bee research and monitoring when integrated into a structured monitoring scheme (Birkin & Goulson, 2015; Kühl et al., 2020; Vereecken et al., 2021). Moreover, citizen science is a valuable tool to stimulate interest in (Ganzevoort & van den Born, 2021) and raise public awareness for wild bees and their conservation (e.g. using trap nests in German schools in the "Schulinsektenhaus" project at the University of Freiburg, https://www.schulinsektenhaus.de). Because of the lack of training, experience, and expertise, however, citizen scientists have been shown to ignore specific groups of wild bees in the field (Kremen et al., 2011) and/or to incorrectly identify large proportions of, for example, bumble bee individuals (Falk et al., 2019; Roy et al., 2016). This needs to be taken into account when working with, and extrapolating from, citizen science data. Citizen science data are also usually opportunistic and unstructured. When such data sets are to be analyzed, for example for occupancy analyses, their predicted suitability needs to be assessed first (Pocock et al., 2019). Furthermore, when bees are identified in the field by citizen scientists and no specimens are collected, findings are difficult to verify and may be unreliable, especially for cryptic species, which are hard or even impossible to identify in the field even for experts (Schmidt et al., 2015; VDI-Richtlinie 4340-1, 2023). Without specific training in bee identification, data from citizen scientists should therefore be restricted to well recognizable species, genera or guilds. Another approach minimizing collector bias is to use observer-independent ("passive") sampling methods and provide citizen scientists with detailed instructions of how, where and when to set up, for example, pan traps or trap nests. They can then contribute to structured wild bee monitoring by collecting specimens which are later identified by experts.

An additional future challenge is that data accessibility is limited, especially regarding the many valuable datasets from non-academic sources, including citizen scientists. Most of these insect collections and sampling data of wild bees are neither published, nor made otherwise accessible, nor even digitized. Explaining why data sharing is important, and offering incentives, such as co-authorships of publications or becoming part of research projects, might help to gain access to such data. Publishing datasets also helps to ensure that property rights are maintained and that the people who conducted the labor-intensive work of monitoring are properly recognized and cited. A prime example of author recognition is the publication on pollinator sampling in gardens during the first COVID-19 lockdown organized by Jeff Ollerton (Ollerton et al., 2022).

Novel methods for studying wild bees

There are several promising new methods currently being developed and tested to sample and identify wild bees (van Klink et al., 2022). In the following, their potential and caveats are discussed.

Using DNA barcoding to identify wild bees, their parasitoids and pollen

The traditional method of visual identification using light microscopy of pinned individuals is labor-intensive and, for many cryptic species, requires a high level of taxonomic expertise that is becoming increasingly rare (e.g. for the *Colletes succinctus* group). Genetic methods have been developed and used, such as DNA barcoding and metabarcoding (barcoding of mixed samples), which allow the identification of species by comparing them to a database containing DNA sequences for the corresponding species (barcodes, e.g. *International Barcode of Life* and *Earth BioGenome Project*) (Creedy et al., 2020; Magnacca & Brown, 2012; Schmidt et al., 2015; Theodorou et al., 2020; Villalta et al., 2021). There are also attempts made at identifying former inhabitants of trap nests non-destructively by genetically analyzing environmental DNA extracted from organismal remnants (e.g. cocoons, exuviae, faeces) after the hosts and their parasitoids have already emerged (e.g. in MonViA project: see Appendix A: Table 1 for details) or from past visitors of flowers (Thomsen & Sigsgaard, 2019). Especially for samples comprising a mix of species, DNA metabarcoding is a promising, time-saving, and cost-efficient method to identify wild bees and their parasitoids. A major problem of DNA metabarcoding still to be addressed is that no reliable quantitative information on species abundances can be obtained (e.g. Bell et al. (2019) for pollen). Also, contamination easily leads to false-positive detections (Zinger et al., 2019). In turn, commonly used primers do not detect all species with the same reliability (Marquina et al., 2019). Furthermore, in many countries, not all species have been barcoded yet. In the case of Germany, all bee species have been barcoded, but their intraspecific divergence can be high (e.g. *Dasypoda hirtipes*; Schmidt et al., 2015), which may prevent correct assignment to a single species. This challenge highlights the need for additional barcodes from specimens of the same species collected in different regions within its range (Schmidt et al., 2015). Such problems with metabarcoding can lead to incomplete species lists, e.g. when species are not detected despite being present in a sample, or when they are assigned to the wrong species (European Commission, Joint

Research Centre, 2021).

Importantly, DNA metabarcoding can also be used to better understand the ecology of bee species. For example, pollen identification by DNA metabarcoding can be used to determine important food sources of bees. DNA metabarcoding and other methods using next generation sequencing are already performing well for qualitative analyses of pollen samples (Gueuning et al., 2019; Keller et al., 2015; Macgregor et al., 2019; Richardson et al., 2015; Smart et al., 2017). If methods are developed further to improve accuracy in quantitative estimates, DNA metabarcoding, and other DNA-based methods such as whole-genome shotgun sequencing (Bell et al., 2021) of pollen will likely become a standard approach to investigate bee-plant interactions, accompanying classical methods (Bell et al., 2016; Pornon et al., 2017). However, plant barcoding also requires a comprehensive database of respective plant DNA sequences, which are still limited for many geographic locations, e.g. the tropics (Bell et al., 2021).

Using artificial intelligence for wild bee and pollen identification

With newly emerging artificial intelligence (AI) approaches, some researchers are optimistic that we will, in the near future, be able to identify wild bees using photographs of live bees taken in the field (Droissart et al., 2021; Høye et al., 2021; Spiesman et al., 2021). Following the example of well-functioning plant identification applications for smart phones (Mäder et al., 2021), bee identification may be achieved in the same way, provided there is a large enough database of bee photographs to train AI algorithms (Spiesman et al., 2021). It is still unclear, however, if this method will also work for identifying the many cryptic species, for example the group of "small, black males" (including many species from the Halictidae family), which even experts cannot visually identify in the field (Hofmann & Renner, 2020; Schmidt et al., 2015; VDI-Richtlinie 4340-1, 2023). Apps identifying at least the most common and distinctive species of wild bees (VDI-Richtlinie 4340-1, 2023) could nevertheless still be a useful tool to increase interest in bees and bee conservation in the general public and to provide more reliable citizen science data (e.g. app "BeeMachine" for North American bumble bees).

Moreover, if newly developed AI technologies were combined with additional methods, such as geometric morphometrics of, for example, the wings (De Meulemeester et al., 2012), and/or acoustic analysis of flight sounds (Kawakita & Ichikawa, 2019), it might even be possible to reliably identify cryptic species. Developing such a multi-method approach would be quite costly in terms of financial and time resources, and may not always be necessary or justifiable, for example, when a complete species list with precise identification of all species is not essential. It may, however, compensate for a lack of expert knowledge when such detailed data are needed.

Besides the DNA-based methods already mentioned, AI and deep learning have also been shown to be applicable for pollen identification using multispectral flow cytometry images, which has extended the classical morphological approach to pollen identification (Dunker et al., 2022).

In summary, even with these and other new tools becoming more reliable, cheaper, and more readily available, classical approaches and expert knowledge on species identification will still be needed in the future to verify results and improve new methods. However, in addition to the limited number of courses offering training for future bee taxonomists, there is also a lack of positions and funding at universities and research institutes to employ them, potentially dissuading interested junior academics from developing taxonomic expertise (Hochkirch et al., 2022).

The potential of wild bee monitoring to evaluate conservation measures

In addition to the identification of general population trends, bee monitoring can be used to evaluate the effectiveness of conservation

Box 2
The role of sampling in bee mortality: Ways to minimize lethal sampling and its impact compared to other factors affecting bee populations

We have recently observed increasing public concerns highlighting ethical problems with sampling insects for research (authors' personal observations, Drinkwater et al., 2019). These concerns stem from a changing public perception of insects, especially pollinators such as bees, which are increasingly seen as beneficial and recognized as threatened and declining. However, bee sampling is necessary for scientific research, in order to be able to become aware of changes in bee communities, detect threats, and develop and evaluate conservation measures. The majority of wild bee species cannot be reliably identified in their vital stage, making lethal sampling necessary.

An intrinsic goal of all bee monitoring programs is to minimize any impact of the sampling itself on bee communities, to avoid masking actual population changes over time. In Germany, all bee monitoring and sampling activities have to be approved by local or national authorities. Approvals are issued considering the scientific value of the data collected, and the potential impact on local populations. Bee sampling has been shown not to affect populations, even when sites are repeatedly sampled for several years, as found by Gezon et al. (2015), who compared bee communities between control sites and sites that were sampled every two weeks over a three year period. Lethal sampling of bees and non-target organisms can be reduced by exposing traps for shorter time periods (e.g. sampling only a few days each at different points in the season, instead of throughout the whole season), using smaller traps, fewer traps per site, switching between sampling locations, and using more specific or non-lethal sampling methods. Furthermore, traps have been shown to catch insects only locally, not drawing in individuals from the wider landscape. For example, Ssymank et al.(2018), found that Malaise traps contained communities specific to the micro-habitat, that differed across distances of as little as 10-20 m. Researchers are also driven to design studies as economically as possible, because resources for sampling and identification of specimens are limited.

Putting bee sampling into perspective, by comparing it to other natural and anthropogenic factors causing bee mortality, its overall impact on bee populations is likely negligible. The insect biomass caught by one malaise trap per season, for example, is equivalent to the food of one young bird per season (Ssymank et al., 2018). In addition, there are anthropogenic factors causing insect mortality either directly (traffic (Keilsohn et al., 2018; Møller, 2013), insecticides, household insect traps) or indirectly (land-use change and herbicides reducing habitat and other resources). These impacts are difficult to quantify exactly, but have been shown to substantially influence populations (Miličić et al., 2021; Potts et al., 2010; Sánchez-Bayo & Wyckhuys, 2019) and are often acting on a large scale and permanently, while bee sampling can impact bees only locally, and in a short time frame. More long-term estimates of potential impacts of repeated wild bee sampling at the same sites require further research, however, which could be informed by data from long-term monitoring schemes. A special case requiring further research, for example, is the potential effect of sampling early in the season, when reproductive individuals of social bee species (e.g. bumble bee queens) are foraging, on the development of their populations in the landscape (Goulson, 2010).

measures. Clear and measurable targets of the measures, and considering both site and landscape characteristics are important requirements here. See Fig. 2 for an overview of external factors influencing the different aspects of a monitoring scheme used to evaluate conservation measures.

The need for clear and measurable targets

It is often unclear when conservation measures can be considered successful (Pe'er et al., 2019). When bee abundance (overall or of specific target species) or species richness at sites where conservation measures have been implemented is compared to past data from the same sites, the measures may only be considered a success when numbers are increasing and/or reach previously recorded numbers. However, slowing down or halting an otherwise steep decline in numbers could also be seen as effective conservation (Bull et al., 2014).

Often, goals and target species of conservation measures are not well defined, which makes it difficult to evaluate their effectiveness (Salafsky et al., 2002). Using data from appropriate monitoring programs, effects can be measured and, when targets have been set, also evaluated. Ideally, sites would already have been part of a monitoring program before measures were implemented, and similar control sites with no measures carried out would also be available (Dicks et al., 2010). Both changes in the community at the site over time, as well as changes in relation to changes at other sites (accounting for potentially confounding factors, such as weather or general trends) can then be assessed, enabling the attribution of changes to the conservation measures implemented.

Considering site and landscape characteristics

The local bee species composition is restricted by the species pool in the landscape (Steffan-Dewenter et al., 2002). Furthermore, the success of one type of conservation measure at different sites can be expected to be highly variable, with differences moderated, for example, by the surrounding landscape (Carvell et al., 2011; Grass et al., 2016). Determining the impact of different local and landscape factors, such as soil, weather, micro-climate, landscape heterogeneity, connectivity, and land-use intensity (Ekroos et al., 2020), on the magnitude of effect is important. Based on the knowledge of site and landscape properties, targets and goals can then be calibrated and the placement and choice of type of conservation measure can be optimized.

Locally, all requirements of a species regarding nesting and food must be met for it to survive and reproduce (Potts et al., 2005; Sardiñas et al., 2016; Steffan-Dewenter & Schiele, 2008). Depending on the type of conservation measure, bee species with different traits (e.g. ground-nesting vs. cavity-nesting or oligolectic vs. polylectic) may be affected differently. If, for example, increasing the availability of food resources was shown to benefit cavity-nesting bees more than ground-nesting bees, this would indicate that additional essential resources were limiting the abundance of ground-nesters, such as the availability of suitable nesting resources.

How monitoring programs can evaluate conservation measures

Depending on the goals of conservation measures, different sampling methods can be most suitable to evaluate the effectiveness of these measures.

For example, there are flower strips composed and planted specifically to provide food for certain oligolectic species of bees. To evaluate these, data regarding germination and flowering quantities of seeded plant species need to be collected. This could be done in collaboration with citizen scientists or farmers, using plant identification applications for smart phones (Mäder et al., 2021). The impact on bee occurrences and numbers can be measured directly, by surveying the food plants and recording interactions with target bee species using targeted hand-netting. Alternatively, effects can be measured indirectly using pan, vane, or malaise traps. Individuals sampled using these methods could then still be directly linked to plants in the flower strip, when pollen can be obtained from the bees' bodies, and analyzed using, for example, DNA barcoding or AI methods. To verify the effects of the type of seed mix used, data must be compared to reference sites, for example, flower strips with different seed mixes (Warzecha et al., 2018). Furthermore, the landscape needs to be considered as a filter, allowing the occurrence of target species, and enabling them to reach the flower strip (Schubert et al., 2022; Warzecha et al., 2021). Results could then be used to further optimize seed mixes for annual and perennial flower strips, adapting them to the region (Bucharova et al., 2022), local conditions, climate, and different target species.

Additional research is needed to evaluate landscape-wide effects of conservation measures. Local effects of added floral resources on bee populations may not represent a landscape-wide population increase, but a concentration of bees in resource-rich areas (Holzschuh et al., 2011). It is unclear, for example, how short-term measures, such as annual flower strips of a consistent total area, but being re-sown every year at different locations, affect bee populations/communities in a

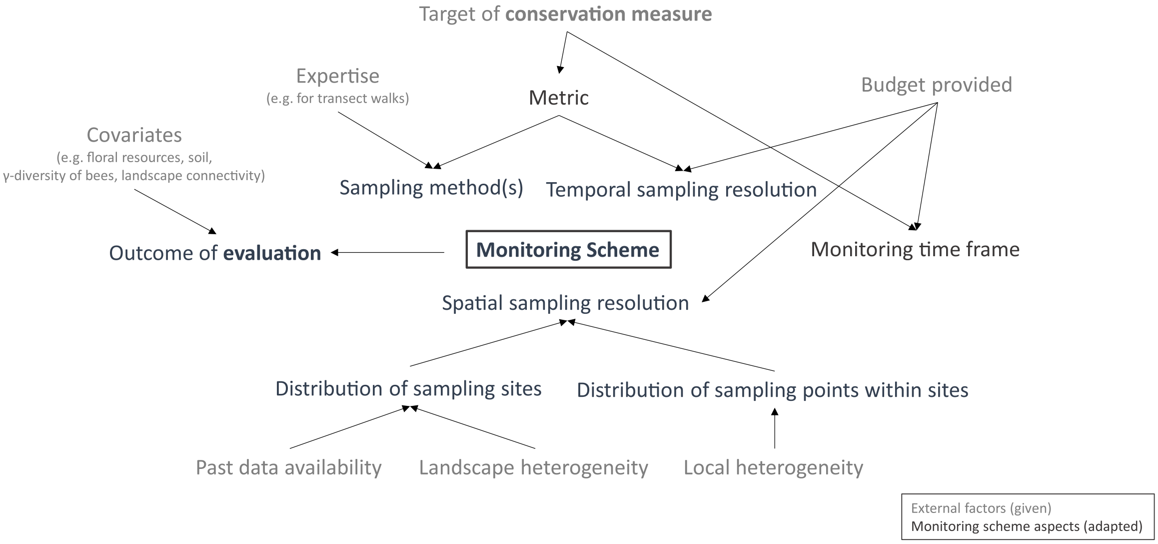


Fig. 2. Conceptual map visualizing aspects important for designing a monitoring scheme for the evaluation of conservation measures.

landscape in the long-term. Furthermore, our knowledge is still limited with regard to how the spatial distribution of, for example, flower strips or nest sites affects the success of these conservation measures. Data from large-scale monitoring schemes covering different regions and landscapes, could help not only to measure the effects of conservation measures, but also to gain understanding about which effects can be expected, how to optimize the placement of measures, and how to facilitate the setting of realistic goals for future conservation programs.

An outlook on future wild bee monitoring

For future bee monitoring programs, we have emphasized the need to use suitable sampling methods depending on the research question, study system, and traits of target species. The local and landscape scales, as well as the temporal resolution and long-term feasibility need to be considered, when designing a monitoring scheme. Methods should be standardized, to make studies and datasets comparable. Citizen scientists can provide additional unstructured sampling data, or be involved in monitoring programs by sampling or even identifying bees. In addition to traditional sampling methods, there are promising novel methods, such as DNA- and AI-based approaches, that may minimize impacts on bee populations and make monitoring faster, and more efficient. Besides the identification of general trends and mechanisms driving populations, bee monitoring programs can also contribute to filling knowledge gaps about potential interactions and synergies among different stressors affecting populations. Furthermore, monitoring programs harbor a great potential to accompany and evaluate the effectiveness of wild bee conservation measures and help to further increase their efficiency.

CRediT authorship contribution statement

Felix Klaus: Conceptualization, Writing – original draft, Writing – review & editing. **Manfred Ayasse:** Writing – review & editing. **Alice Classen:** Writing – review & editing. **Jens Dauber:** Writing – review & editing. **Tim Diekötter:** Writing – review & editing. **Jeroen Everaars:** Writing – review & editing. **Felix Fornoff:** Writing – review & editing. **Henri Greil:** Conceptualization, Writing – review & editing. **Harmen P. Hendriksma:** Conceptualization, Writing – review & editing. **Tobias Jütte:** Conceptualization, Writing – review & editing. **Alexandra Maria Klein:** Writing – review & editing. **André Krahner:** Conceptualization, Writing – review & editing. **Sara D. Leonhardt:** Writing – review & editing. **Dorothee J. Lüken:** Conceptualization, Writing – review & editing. **Robert J. Paxton:** Writing – review & editing. **Christian Schmid-Egger:** Writing – review & editing. **Ingolf Steffan-Dewenter:** Writing – review & editing. **Jan Thiele:** Writing – review & editing. **Teja Tscharntke:** Writing – review & editing. **Silvio Erler:** Conceptualization, Supervision, Writing – review & editing. **Jens Pistorius:** Conceptualization, Supervision, Writing – review & editing.

Declarations of competing interest

None.

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Supplementary materials

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References

Assembly U.G., & Committee 2nd. (2003). Environment and sustainable development: Convention on biological diversity: Report of the 2nd Committee: General Assembly, 58th session.

Bell, K. L., De Vere, N., Keller, A., Richardson, R. T., Gous, A., Burgess, K. S., & Brosi, B. J. (2016). Pollen DNA barcoding: Current applications and future prospects. *Genome, 59*(9), 629–640.

Bell, K. L., Burgess, K. S., Botsch, J. C., Dobbs, E. K., Read, T. D., & Brosi, B. J. (2019). Quantitative and qualitative assessment of pollen DNA metabarcoding using constructed species mixtures. *Molecular Ecology, 28*(2), 431–455.

Bell, K. L., Petit, I. I. I., R, A., Cutler, A., Dobbs, E. K., Macpherson, J. M., Read, T. D., Burgess, K. S., & Brosi, B. J (2021). Comparing whole-genome shotgun sequencing and DNA metabarcoding approaches for species identification and quantification of pollen species mixtures. *Ecology and Evolution, 11*(22), 16082–16098.

Birkin, L., & Goulson, D. (2015). Using citizen science to monitor pollination services. *Ecological Entomology, 40*, 3–11.

Bittner, T., Theves, F., Bindrich, F., Reischke, N., & Paton, C. (2020). *Das biodiversitätsmonitoring der landesanstalt für umwelt baden-Württemberg.* LUBW Landesanstalt für Umwelt Baden-Württemberg.

Breeze, T. D., Bailey, A. P., Balcombe, K. G., Brereton, T., Comont, R., Edwards, M., Garratt, M. P., Harvey, M., Hawes, C., & Isaac, N. (2021). Pollinator monitoring more than pays for itself. *Journal of Applied Ecology, 58*(1), 44–57.

Bucharova, A., Lampei, C., Conrady, M., May, E., Matheja, J., Meyer, M., & Ott, D. (2022). Plant provenance affects pollinator network: Implications for ecological restoration. *Journal of Applied Ecology, 59*(2), 373–383.

Bull, J. W., Gordon, A., Law, E. A., Suttle, K. B., & Milner-Gulland, E. J. (2014). Importance of baseline specification in evaluating conservation interventions and achieving no net loss of biodiversity. *Conservation Biology, 28*(3), 799–809. https://doi.org/10.1111/cobi.12243

Cane, J. (2021). Global warming, advancing bloom and evidence for pollinator plasticity from long-term bee emergence monitoring. *Insects, 12*(5), 457.

Carvell, C., Osborne, J. L., Bourke, A. F. G., Freeman, S. N., Pywell, R. F., & Heard, M. S. (2011). Bumble bee species’ responses to a targeted conservation measure depend on landscape context and habitat quality. *Ecological Applications, 21*(5), 1760–1771.

Cf O. (2015). Transforming our world: The 2030 agenda for sustainable development. United Nations: New York, NY, USA.

Cole, L. J., Kleijn, D., Dicks, L. V., Stout, J. C., Potts, S. G., Albrecht, M., Balzan, M. V., Bartomeus, I., Bebeli, P. J., & Bevk, D. (2020). A critical analysis of the potential for EU common agricultural policy measures to support wild pollinators on farmland. *Journal of Applied Ecology, 57*(4), 681–694.

Corbet, S. A., Williams, I. H., & Osborne, J. L. (1991). Bees and the pollination of crops and wild flowers in the European Community. *Bee World, 72*(2), 47–59.

Creedy, T. J., Norman, H., Tang, C. Q., Qing Chin, K., Andujar, C., Arribas, P., O’Connor, R. S., Carvell, C., Notton, D. G., & Vogler, A. P. (2020). A validated workflow for rapid taxonomic assignment and monitoring of a national fauna of bees (Apiformes) using high throughput DNA barcoding. *Molecular Ecology Resources, 20*(1), 40–53.

De Meulemeester, T., Michez, D., Aytekin, A. M., & Danforth, B. N. (2012). Taxonomic affinity of halictid bee fossils (Hymenoptera: Anthophila) based on geometric morphometrics analyses of wing shape. *Journal of Systematic Palaeontology, 10*(4), 755–764.

Dicks, L. V., Showler, D. A., & Sutherland, W. J. (2010). *Bee conservation: Evidence for the effects of interventions*. Pelagic Publishing.

Dicks, L. V., Breeze, T. D., Ngo, H. T., Senapathi, D., An, J., Aizen, M. A., Basu, P., Buchori, D., Galetto, L., & Garibaldi, L. A. (2021). A global-scale expert assessment of drivers and risks associated with pollinator decline. *Nature ecology & evolution*, 1–9.

Drinkwater, E., Robinson, E. J., & Hart, A. G. (2019). Keeping invertebrate research ethical in a landscape of shifting public opinion. *Methods in Ecology and Evolution, 10*(8), 1265–1273.

Droissart, V., Azandi, L., Onguene, E. R., Savignac, M., Smith, T. B., & Deblauwe, V. (2021). PICT: A low-cost, modular, open-source camera trap system to study plant–insect interactions. *Methods in Ecology and Evolution, 12*(8), 1389–1396.

Duelli, P., Obrist, M. K., & Schmatz, D. R. (1999). Biodiversity evaluation in agricultural landscapes: Above-ground insects. *Agriculture, Ecosystems & Environment, 74*(1–3), 33–64.

Dunker, S., Boyd, M., Durka, W., Erler, S., Harpole, W. S., Henning, S., Herzschuh, U., Hornick, T., Knight, T., & Lips, S. (2022). The potential of multispectral imaging flow cytometry for environmental monitoring. *Cytometry Part A, 101*(9), 782–799.

Ekroos, J., Kleijn, D., Batáry, P., Albrecht, M., Báldi, A., Blüthgen, N., Knop, E., Kovács-Hostyánszki, A., & Smith, H. G. (2020). High land-use intensity in grasslands constrains wild bee species richness in Europe. *Biological Conservation, 241*, Article 108255.

Espín, S., García-Fernández, A. J., Herzke, D., Shore, R. F., Van Hattum, B., Martínez-López, E., Coeurdassier, M., Eulaers, I., Fritsch, C., Gómez-Ramírez, P., Jaspers, V. L. B., Krone, O., Duke, G., Helander, B., Mateo, R., Movalli, P., Sonne, C., & Van Den Brink, N. W (2016). Tracking pan-continental trends in environmental contamination using sentinel raptors—what types of samples should we use? *Ecotoxicology, 25*(4), 777–801. https://doi.org/10.1007/s10646-016-1636-8

European Commission, Joint Research Centre. (2021). *Proposal for an EU pollinator monitoring scheme*. https://data.europa.eu/doi/10.2760/881843.

Falk, S., Foster, G., Comont, R., Conroy, J., Bostock, H., Salisbury, A., Kilbey, D., Bennett, J., & Smith, B. (2019). Evaluating the ability of citizen scientists to identify bumblebee (Bombus) species. *PLOS One, 14*(6), Article e0218614.

Fournier, A. M. V., White, E. R., & Heard, S. B. (2019). Site-selection bias and apparent population declines in long-term studies. *Conservation Biology, 33*(6), 1370–1379. https://doi.org/10.1111/cobi.13371

Ganzevoort, W., & van den Born, R. J. (2021). Counting bees: Learning outcomes from participation in the Dutch national bee survey. *Sustainability, 13*(9), 4703.

Gezon, Z. J., Wyman, E. S., Ascher, J. S., Inouye, D. W., & Irwin, R. E. (2015). The effect of repeated, lethal sampling on wild bee abundance and diversity. *Methods in Ecology and Evolution, 6*(9), 1044–1054.

Goldsmith, F. B. (2012). *Monitoring for conservation and ecology (Bd. 3)*. Springer Science & Business Media. https://books.google.com/books?hl=de&lr=&id=8RjRBgAAQBAJ&oi=fnd&pg=PR9&dq=monitoring+for+conservation+and+ecology&ots=LhD19LvBTQ&sig=e2rwN3S5FaX8xvg4-IoxYQtwOGU.

Goulson, D., Nicholls, E., Botías, C., & Rotheray, E. L. (2015). Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science*, (6229), 347.

Goulson, D. (2010). *Bumblebees: Behaviour, ecology, and conservation*. Oxford University Press. https://books.google.com/books?hl=de&lr=&id=F6wVDAAAQBAJ&oi=fnd&pg=PR5&dq=Bumblebees+Behaviour,+Ecology,+and+Conservation&ots=_4NpxzayyX&sig=I249fwRktAYRoWX0thlYFViNcNk.

Grass, I., Albrecht, J., Jauker, F., Diekötter, T., Warzecha, D., Wolters, V., & Farwig, N. (2016). Much more than bees—Wildflower plantings support highly diverse flower-visitor communities from complex to structurally simple agricultural landscapes. *Agriculture, Ecosystems & Environment, 225*, 45–53.

Gueuning, M., Ganser, D., Blaser, S., Albrecht, M., Knop, E., Praz, C., & Frey, J. E. (2019). Evaluating next-generation sequencing (NGS) methods for routine monitoring of wild bees: Metabarcoding, mitogenomics or NGS barcoding. *Molecular Ecology Resources, 19*(4), 847–862.

Høye, T. T., Ärje, J., Bjerge, K., Hansen, O. L., Iosifidis, A., Leese, F., … Raitoharju, J. (2021). Deep learning and computer vision will transform entomology. *Proceedings of the National Academy of Sciences, 118*(2), Article e2002545117.

Halvorson, K., Baumung, R., Leroy, G., Chen, C., & Boettcher, P. (2021). Protection of honeybees and other pollinators: One global study. *Apidologie*, 1–13.

Harrop, S. R. (2011). 'Living in harmony with nature'? Outcomes of the 2010 nagoya conference of the convention on biological diversity. *Journal of Environmental Law, 23*(1), 117–128.

Hochkirch A., Casino A., Penev L., Allen D., Tilley L., Georgiev T., Gospodinov K., & Barov B. (2022). European red list of insect taxonomists. publications office of the european union, luxembourg.

Hofmann, M. M., & Renner, S. S. (2020). Bee species decrease and increase between the 1990s and 2018 in large urban protected sites. *Journal of Insect Conservation, 24*(4), 637–642.

Holzschuh, A., Dormann, C. F., Tscharntke, T., & Steffan-Dewenter, I. (2011). Expansion of mass-flowering crops leads to transient pollinator dilution and reduced wild plant pollination. *Proceedings of the Royal Society B: Biological Sciences, 278*(1723), 3444–3451.

Hribar, L. J. (2020). Expanding basic entomological knowledge by using mosquito surveillance bycatch. *Annals of the Entomological Society of America, 113*(6), 439–446.

Kühl, H. S., Bowler, D. E., Bösch, L., Bruelheide, H., Dauber, J., Eichenberg, D., Eisenhauer, N., Fernández, N., Guerra, C. A., Henle, K., Herbinger, I., Isaac, N. J. B., Jansen, F., König-Ries, B., Kühn, I., Nilsen, E. B., Pe'er, G., Richter, A., Schulte, R., …, & Bonn, A. (2020). Effective biodiversity monitoring needs a culture of integration. *One Earth, 3*(4), 462–474. https://doi.org/10.1016/j.oneear.2020.09.010

Kawakita, S., & Ichikawa, K. (2019). Automated classification of bees and hornet using acoustic analysis of their flight sounds. *Apidologie, 50*(1), 71–79.

Keilsohn, W., Narango, D. L., & Tallamy, D. W. (2018). Roadside habitat impacts insect traffic mortality. *Journal of Insect Conservation, 22*(2), 183–188.

Keller, A., Danner, N., Grimmer, G., Ankenbrand, Von Der Ohe, K., Von Der Ohe, W., Rost, S., Härtel, S., & Steffan-Dewenter, I. (2015). Evaluating multiplexed next-generation sequencing as a method in palynology for mixed pollen samples. *Plant Biology, 17*(2), 558–566.

Kendall, L. K., Mola, J. M., Portman, Z. M., Cariveau, D. P., Smith, H. G., & Bartomeus, I. (2022). The potential and realized foraging movements of bees are differentially determined by body size and sociality. *Ecology, 103*(11), e3809. https://doi.org/10.1002/ecy.3809

Klein, A. M., Vaissiere, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences, 274*(1608), 303–313.

Krahner, A., Schmidt, J., Maixner, M., Porten, M., & Schmitt, T. (2021). Evaluation of four different methods for assessing bee diversity as ecological indicators of agro-ecosystems. *Ecological Indicators, 125*, Article 107573.

Kremen, C., Ullman, K. S., & Thorp, R. W. (2011). Evaluating the quality of citizen-scientist data on pollinator communities. *Conservation Biology, 25*(3), 607–617.

Larigauderie, A., & Mooney, H. A. (2010). The intergovernmental science-policy platform on biodiversity and ecosystem services: Moving a step closer to an IPCC-like mechanism for biodiversity. *Current Opinion in Environmental Sustainability, 2*(1–2), 9–14.

Larsson, M., & Franzen, M. (2008). Estimating the population size of specialised solitary bees. *Ecological Entomology, 33*(2), 232–238.

Mäder, P., Boho, D., Rzanny, M., Seeland, M., Wittich, H. C., Deggelmann, A., & Wäldchen, J. (2021). The flora incognita app–interactive plant species identification. *Methods in Ecology and Evolution, 12*, 1335–1342.

Møller, A. P. (2013). Long-term trends in wind speed, insect abundance and ecology of an insectivorous bird. *Ecosphere, 4*(1), 1–11.

Macgregor, C. J., Kitson, J. J., Fox, R., Hahn, C., Lunt, D. H., Pocock, M. J., & Evans, D. M. (2019). Construction, validation, and application of nocturnal pollen transport networks in an agro-ecosystem: A comparison using light microscopy and DNA metabarcoding. *Ecological Entomology, 44*(1), 17–29.

Magnacca, K. N., & Brown, M. J. (2012). DNA barcoding a regional fauna: Irish solitary bees. *Molecular Ecology Resources, 12*(6), 990–998.

Marquina, D., Andersson, A. F., & Ronquist, F. (2019). New mitochondrial primers for metabarcoding of insects, designed and evaluated using in silico methods. *Molecular Ecology Resources, 19*(1), 90–104.

Miličić, M., Popov, S., Branco, V. V., & Cardoso, P. (2021). Insect threats and conservation through the lens of global experts. *Conservation Letters, 14*(4), e12814.

Montgomery, G. A., Belitz, M. W., Guralnick, R. P., & Tingley, M. W. (2021). Standards and best practices for monitoring and benchmarking insects. *Frontiers in Ecology and Evolution, 8*, 513.

Nieto A., Roberts S.P., Kemp J., Rasmont P., Kuhlmann M., Criado M.G., Biesmeijer J.C., Bogusch P., Dathe H.H., & De la Rúa P. (2017) European red list of bees.

Ollerton, J., Winfree, R., & Tarrant, S. (2011). How many flowering plants are pollinated by animals? *Oikos, 120*(3), 321–326.

Ollerton, J., Trunschke, J., Havens, K., Landaverde-González, P., Keller, A., Gilpin, A. M., Rech, A. R., Baronio, G. J., Phillips, B. J., & Mackin, C. (2022). Pollinator-flower interactions in gardens during the COVID-19 pandemic lockdown of 2020. *Journal of Pollination Ecology, 31*, 87–96.

Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., & Fernández-Ugalde, O. (2018). LUCAS Soil, the largest expandable soil dataset for Europe: A review. *European Journal of Soil Science, 69*(1), 140–153. https://doi.org/10.1111/ejss.12499

Pe'er, G., Zinngrebe, Y., Moreira, F., Sirami, C., Schindler, S., Müller, R., Bontzorlos, V., Clough, D., Bezák, P., & Bonn, A. (2019). A greener path for the EU common agricultural Policy. *Science, 365*(6452), 449–451.

Pocock, M. J., Logie, M. W., Isaac, N. J., Outhwaite, C. L., & August, T. (2019). Rapid assessment of the suitability of multi-species citizen science datasets for occupancy trend analysis. *BioRxiv*, Article 813626.

Pollard, E., Yates, T. J., & Courtney, S. P. (1994). Monitoring butterflies for ecology and conservation: The British butterfly monitoring scheme. *Ecology, 75*(6), 1851.

Pornon, A., Andalo, C., Burrus, M., & Escaravage, N. (2017). DNA metabarcoding data unveils invisible pollination networks. *Scientific Reports, 7*(1), 1–11.

Portman, Z. M., Bruninga-Socolar, B., & Cariveau, D. P. (2020). The state of bee monitoring in the United States: A call to refocus away from bowl traps and towards more effective methods. *Annals of the Entomological Society of America, 113*(5), 337–342.

Potts, S. G., Vulliamy, B., Roberts, S., O'Toole, C., Dafni, A., Ne'eman, G., & Willmer, P. (2005). Role of nesting resources in organising diverse bee communities in a Mediterranean landscape. *Ecological Entomology, 30*(1), 78–85.

Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O., & Kunin, W. E. (2010). Global pollinator declines: Trends, impacts and drivers. *Trends in Ecology & Evolution, 25*(6), 345–353.

Potts, S. G., Imperatriz-Fonseca, V., Ngo, H. T., Biesmeijer, J. C., Breeze, T. D., Dicks, L. V., Garibaldi, L. A., Hill, R., Settele, J.Vanbergen, A. J., … (2016). *The assessment report on pollinators, pollination and food production: Summary for policymakers.* Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity.

Potts, S., Dauber, J., Hochkirch, A., Oteman, B., Roy, D., Ahnre, K., Biesmeijer, K., Breeze, T., Carvell, C., Ferreira, C., Úna, F., Isaac, N., Kuussaari, M., Ljubomirov, T., Maes, J., Ngo, H., Pardo, A., Polce, C., Quaranta, M., …, & Vujic, A. (2021). Proposal for an EU pollinator monitoring scheme. *JRC Publications Repository*. https://doi.org/10.2760/881843

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.

Prado, S. G., Ngo, H. T., Florez, J. A., & Collazo, J. A. (2017). Sampling bees in tropical forests and agroecosystems: A review. *Journal of Insect Conservation, 21*(5–6), 753–770. https://doi.org/10.1007/s10841-017-0018-8

Prendergast, K. S., Menz, M. H., Dixon, K. W., & Bateman, P. W. (2020). The relative performance of sampling methods for native bees: An empirical test and review of the literature. *Ecosphere, 11*(5), e03076.

Richardson, R. T., Lin, C. H., Sponsler, D. B., Quijia, J. O., Goodell, K., & Johnson, R. M. (2015). Application of ITS2 metabarcoding to determine the provenance of pollen collected by honey bees in an agroecosystem. *Applications in Plant Sciences, 3*(1), Article 1400066.

Roy, H. E., Baxter, E., Saunders, A., & Pocock, M. J. (2016). Focal plant observations as a standardised method for pollinator monitoring: Opportunities and limitations for mass participation citizen science. *PLOS One, 11*(3), Article e0150794.

Sánchez-Bayo, F., & Wyckhuys, K. A. (2019). Worldwide decline of the entomofauna: A review of its drivers. *Biological Conservation, 232*, 8–27.

Salafsky, N., Margoluis, R., Redford, K. H., & Robinson, J. G. (2002). Improving the practice of conservation: A conceptual framework and research agenda for conservation science. *Conservation Biology, 16*(6), 1469–1479.

Sardiñas, H. S., Tom, K., Ponisio, L. C., Rominger, A., & Kremen, C. (2016). Sunflower (Helianthus annuus) pollination in California's central valley is limited by native bee nest site location. *Ecological Applications, 26*(2), 438–447.

Scherber, C., Beduschi, T., & Tscharntke, T. (2019). Novel approaches to sampling pollinators in whole landscapes: A lesson for landscape-wide biodiversity monitoring. *Landscape Ecology, 34*(5), 1057–1067. https://doi.org/10.1007/s10980-018-0757-2

Schindler, M., Diestelhorst, O., Haertel, S., Saure, C., Scharnowski, A., & Schwenninger, H. R. (2013). Monitoring agricultural ecosystems by using wild bees as environmental indicators. *BioRisk, 8*, 53.

Schmidt, S., Schmid-Egger, C., Morinière, J., Haszprunar, G., & Hebert, P. D. (2015). DNA barcoding largely supports 250 years of classical taxonomy: Identifications for central european bees (hymenoptera, apoidea partim). *Molecular Ecology Resources, 15*(4), 985–1000.

Schubert, L. F., Hellwig, N., Kirmer, A., Schmid-Egger, C., Schmidt, A., Dieker, P., & Tischew, S. (2022). Habitat quality and surrounding landscape structures influence wild bee occurrence in perennial wildflower strips. *Basic and Applied Ecology, 60*, 76–86.

Smart, M. D., Cornman, R. S., Iwanowicz, D. D., McDermott-Kubeczko, M., Pettis, J. S., Spivak, M. S., & Otto, C. R. (2017). A comparison of honey bee-collected pollen from working agricultural lands using light microscopy and ITS metabarcoding. *Environmental Entomology, 46*(1), 38–49.

Spears, L. R., & Ramirez, R. A. (2015). Learning to love leftovers: Using by-catch to expand our knowledge in entomology. *American Entomologist, 61*(3), 168–173.

Spiesman, B. J., Gratton, C., Hatfield, R. G., Hsu, W. H., Jepsen, S., McCornack, B., Patel, K., & Wang, G. (2021). Assessing the potential for deep learning and computer vision to identify bumble bee species from images. *Scientific Reports, 11*(1), 1–10.

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.* Entomologischer Verein Krefeld.

Steffan-Dewenter, I., & Schiele, S. (2008). Do resources or natural enemies drive bee population dynamics in fragmented habitats. *Ecology, 89*(5), 1375–1387.

Steffan-Dewenter, I., Münzenberg, U., Bürger, C., Thies, C., & Tscharntke, T. (2002). Scale-dependent effects of landscape context on three pollinator guilds. *Ecology, 83*(5), 1421–1432.

Sutter, L., Jeanneret, P., Bartual, A. M., Bocci, G., & Albrecht, M. (2017). Enhancing plant diversity in agricultural landscapes promotes both rare bees and dominant crop-pollinating bees through complementary increase in key floral resources. *Journal of Applied Ecology, 54*(6), 1856–1864.

Templ, B., Mózes, E., Templ, M., Földesi, R., Szirák, Á., Báldi, A., & Kovács-Hostyánszki, A. (2019). Habitat-dependency of transect walk and pan trap methods for bee sampling in farmlands. *Journal of Apicultural Science, 63*(1), 93–115.

Tepedino, V. J., & Portman, Z. M. (2021). Intensive monitoring for bees in North America: Indispensable or improvident? *Insect Conservation and Diversity*.

Theodorou, P., Radzevičiūtė, R., Lentendu, G., Kahnt, B., Husemann, M., Bleidorn, C., Settele, J., Schweiger, O., Grosse, I., & Wubet, T. (2020). Urban areas as hotspots for bees and pollination but not a panacea for all insects. *Nature Communications, 11*(1), 1–13.

Thompson, A., Frenzel, M., Schweiger, O., Musche, M., Groth, T., Roberts, S. P., Kuhlmann, M., & Knight, T. M. (2021). Pollinator sampling methods influence community patterns assessments by capturing species with different traits and at different abundances. *Ecological Indicators, 132*, Article 108284.

Thomsen, P. F., & Sigsgaard, E. E. (2019). Environmental DNA metabarcoding of wild flowers reveals diverse communities of terrestrial arthropods. *Ecology and Evolution, 9*(4), 1665–1679.

van Klink, R., August, T., Bas, Y., Bodesheim, P., Bonn, A., Fossøy, F., Høye, T. T., Jongejans, E., Menz, M. H., & Miraldo, A. (2022). Emerging technologies revolutionise insect ecology and monitoring. *Trends in Ecology & Evolution*.

VDI-Richtlinie 4340-1 (2023) Standardisierte bestandsschonende erfassung von wildbienen für ein langzeitmonitoring. Verein Deutscher Ingenieure e.V., Düsseldorf https://www.vdi.de/richtlinien/details/vdi-4340-blatt-1-biodiversitaet-standardisierte-bestandsschonende-erfassung-von-wildbienen-fuer-ein-langzeitmonitoring.

Vereecken, N. J., Weekers, T., Marshall, L., D'Haeseleer, J., Cuypers, M., Pauly, A., Pasau, B., Leclercq, N., Tshibungu, A., & Molenberg, J. M. (2021). Five years of citizen science and standardised field surveys in an informal urban green space reveal a threatened Eden for wild bees in Brussels, Belgium. *Insect Conservation and Diversity*.

Villalta, I., Ledet, R., Baude, M., Genoud, D., Bouget, C., Cornillon, M., Moreau, S., Courtial, B., & Lopez-Vaamonde, C. (2021). A DNA barcode-based survey of wild urban bees in the Loire Valley, France. *Scientific Reports, 11*(1), 1–10.

Warzecha, D., Diekötter, T., Wolters, V., & Jauker, F. (2018). Attractiveness of wildflower mixtures for wild bees and hoverflies depends on some key plant species. *Insect Conservation and Diversity, 11*(1), 32–41.

Warzecha, D., Diekötter, T., Wolters, V., & Jauker, F. (2021). Spatial configuration and landscape context of wildflower areas determine their benefits to pollinator α-and β-diversity. *Basic and Applied Ecology, 56*, 335–344.

Watson R., Baste I., Larigauderie A., Leadley P., Pascual U., Baptiste B., Demissew S., Dziba L., Erpul G., & Fazel A. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. Bonn, Germany: IPBES Secretariat.

Weber, M., Diekötter, T., Dietzsch, A. C., Erler, S., Greil, H., Jütte, T., Krahner, A., & Pistorius, J. (2023). Urban wild bees benefit from flower-rich anthropogenic land use depending on bee trait and scale. *Landscape Ecology, 38*(11), 2981–2999. https://doi.org/10.1007/s10980-023-01755-2

Westphal, C., Bommarco, R., Carré, G., Lamborn, E., Morison, N., Petanidou, T., Potts, S. G., Roberts, S. P., Szentgyörgyi, H., & Tscheulin, T. (2008). Measuring bee diversity in different European habitats and biogeographical regions. *Ecological Monographs, 78*(4), 653–671.

Westrich, P. (2019). *Die wildbienen deutschlands (2., aktualisierte auflage)*. Ulmer, Stuttgart.

Woodard, S. H., Federman, S., James, R. R., Danforth, B. N., Griswold, T. L., Inouye, D., McFrederick, Q. S., Morandin, L., Paul, D. L., & Sellers, E. (2020). Towards a US national program for monitoring native bees. *Biological Conservation, 252*, Article 108821.

Zacharias, S., Bogena, H., Samaniego, L., Mauder, M., Fuß, R., Pütz, T., Frenzel, M., Schwank, M., Baessler, C., & Butterbach-Bahl, K. (2011). A network of terrestrial environmental observatories in Germany. *Vadose Zone Journal, 10*(3), 955–973.

Zattara, E. E., & Aizen, M. A. (2021). Worldwide occurrence records suggest a global decline in bee species richness. *One Earth, 4*(1), 114–123.

Zinger, L., Bonin, A., Alsos, I. G., Bálint, M., Bik, H., Boyer, F., Chariton, A. A., Creer, S., Coissac, E., & Deagle, B. E. (2019). DNA metabarcoding—need for robust experimental designs to draw sound ecological conclusions. *Molecular ecology (Bd. 28, Nummer 8, S. 1857–1862)*. Wiley Online Library.

Further reading

Acharya, R. S., Leslie, T., Fitting, E., Burke, J., Loftin, K., & Joshi, N. K. (2021). Color of pan trap influences sampling of bees in livestock pasture ecosystem. *Biology, 10*(5), 445.

Cope, G. C., Campbell, J. W., Grodsky, S. M., & Ellis, J. D. (2019). Evaluation of nest-site selection of ground-nesting bees and wasps (Hymenoptera) using emergence traps. *Canadian Entomologist, 151*(2), 260–271.

Geroff, R. K., Gibbs, J., & McCravy, K. W. (2014). Assessing bee (Hymenoptera: Apoidea) diversity of an Illinois restored tallgrass prairie: Methodology and conservation considerations. *Journal of Insect Conservation, 18*(5), 951–964.

Hall, M. (2018). Blue and yellow vane traps differ in their sampling effectiveness for wild bees in both open and wooded habitats. *Agricultural and Forest Entomology, 20*(4), 487–495.

Hopfenmüller, S., Holzschuh, A., & Steffan-Dewenter, I. (2020). Effects of grazing intensity, habitat area and connectivity on snail-shell nesting bees. *Biological Conservation, 242*, 108406.

Hutchinson, L.A., Oliver, T.H., Breeze, T.D., O'Connor, R.S., Potts, S.G., Roberts, S.P., & Garratt, M.P (2022). Inventorying and monitoring crop pollinating bees: Evaluating the effectiveness of common sampling methods. Insect Conservation and Diversity, 15(3), 299–311.

Joshi, N. K., Leslie, T., Rajotte, E. G., Kammerer, M. A., Otieno, M., & Biddinger, D. J. (2015). Comparative trapping efficiency to characterize bee abundance, diversity, and community composition in apple orchards. *Annals of the Entomological Society of America, 108*(5), 785–799.

Leclercq, N., Marshall, L., Weekers, T., Anselmo, A., Benda, D., Bevk, D., … Galloni, M. (2022). A comparative analysis of crop pollinator survey methods along a large-scale climatic gradient. *Agriculture, Ecosystems & Environment, 329*, 107871.

McCravy, K. W., Geroff, R. K., & Gibbs, J. (2019). Bee (Hymenoptera: Apoidea: Anthophila) functional traits in relation to sampling methodology in a restored tallgrass prairie. *Florida Entomologist, 102*(1), 134–140.

Neumüller, U., Burger, H., Krausch, S., Blüthgen, N., & Ayasse, M. (2020). Interactions of local habitat type, landscape composition and flower availability moderate wild bee communities. *Landscape Ecology, 35*(10), 2209–2224.

O'Connor, R. S., Kunin, W. E., Garratt, M. P. D., Potts, S. G., Roy, H. E., Andrews, C., … Carvell, C. (2019). Monitoring insect pollinators and flower visitation: The effectiveness and feasibility of different survey methods. *Methods in Ecology and Evolution, 10*(12), 2129–2140. https://doi.org/10.1111/2041-210X.13292

Pane, A. M., & Harmon-Threatt, A. N. (2017). An assessment of the efficacy and peak catch rates of emergence tents for measuring bee nesting. *Applications in Plant Sciences, 5*(6), 1700007.

Sardinas, H. S., & Kremen, C. (2014). Evaluating nesting microhabitat for ground-nesting bees using emergence traps. *Basic and Applied Ecology, 15*(2), 161–168.

Staab, M., Pufal, G., Tscharntke, T., & Klein, A. M. (2018). Trap nests for bees and wasps to analyse trophic interactions in changing environments—a systematic overview and user guide. *Methods in Ecology and Evolution, 9*(11), 2226–2239.

Tscharntke, T., Gathmann, A., & Steffan-Dewenter, I. (1998). Bioindication using trap-nesting bees and wasps and their natural enemies: Community structure and interactions. *Journal of Applied Ecology, 35*(5), 708–719.