CITIZEN SCIENCE:
THEORY AND PRACTICE

Citizen Science-Based Monitoring of Cavity-Nesting Wild Bees and Wasps – Benefits for Volunteers, Insects, and Ecological Science

RESEARCH PAPER

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LARA LINDERMANN
SWANTJE GRABENER
NIELS HELLWIG
JOHANNA STAHL
PETRA DIEKER

*Author affiliations can be found in the back matter of this article

ABSTRACT

Citizen science approaches are promising for raising awareness about the sensitivity of pollinators to environmental changes and simultaneously gathering data about their biology. Questions remain, however, about citizens' ability to gather accurate data. Here, we present a citizen science monitoring approach of cavity-nesting wild bees and wasps in agricultural landscapes across Germany. By using nesting observation blocks (NOBs), which consist of individual wooden boards screwed together, volunteers record the colonisation and development of cavity-nesting Hymenoptera. To do this, they open the NOBs monthly and photograph each board individually. We tested if volunteers can be trained to accurately identify taxa from photographs by offering identification courses and an online quiz. For that purpose, twelve volunteers without taxonomic knowledge identified and counted larvae and cocoons of wild bees and wasps in 4,203 occupied cavities: 92.4% were correctly identified, 4.8% were incorrectly identified, and 2.8% were unidentifiable by experts. These results indicated that volunteers unfamiliar with these taxonomic groups successfully gained a high level of knowledge within one season supported by identification trainings. Using Wald chi-square tests, successful identification was mainly affected by the variability of the taxon. In view of increasing public demand for habitat restoration to halt and counteract declining pollinator populations, the proposed citizen science monitoring approach offers an opportunity for every interested citizen, regardless of their background knowledge, to engage with wild bees and wasps, and gain knowledge about their ecology.

CORRESPONDING AUTHOR:
Lara Lindermann
Thuenen Institute of Biodiversity, DE
lara.lindermann@thuenen.de

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INTRODUCTION

Insect populations are experiencing global declines despite their importance for ecosystem function and services. Consequently, large efforts have been undertaken over past decades to understand the ecology of insects and their population development to adapt management practices and development conservation measures (Pyle et al. 1981; Samways 2007). In this context, involving nongovernmental organisations alongside public institutions in monitoring activities has been considered a constitutive strategy (Settele et al. 2008). On the one hand, it supports large-scale data collection and increases taxonomic knowledge (e.g., Xerces Society, Butterfly Conservation, and Buglife; Samways 2018). On the other hand, it raises awareness about insects' sensitivity to environmental changes. In particular, Hallmann et al. (2017) managed to bring the issue of insect decline into mainstream conversation (European Commission 2018; German Federal Ministry for the Environment 2021). Since then, numerous initiatives reflect citizens' desire to engage in projects for insect conservation and in particular for pollinators such as wild bees (e.g., Krack and Oberholzer 2020). The lack of standardised long-term data on their abundance and diversity, however, makes it difficult to estimate the scale, extent, and driving forces of pollinator decline (Powney et al. 2019). As a result, authorities across scales have increasingly recognised the need for surveying pollinators (Potts et al. 2021). At the same time, numerous studies are adopting citizen science–based monitoring approaches (e.g., Kremen et al. 2011; Mason and Arathi 2019; Comont and Dickinson 2022; Wagner et al. 2021). These monitoring programmes offer volunteers a variety of ways to engage with and gain knowledge about ecology, biology, and conservation of specific taxonomic groups of pollinators, and are thus in line with political demands for supporting civil engagement (Potts et al. 2021).

So far, numerous surveys to estimate abundance and species diversity of wild bees and wasps have been based on trap types that involve killing insects for species identification (Westphal et al. 2008). These approaches are preferably applied, although alternatives are already known. Lethal methods stand in contrast to the intention and desire of citizens to save bees, so these sampling methods are nonsensical (Boes 2021) and may even reduce willingness to participate. Non-lethal sampling may reduce the barrier for volunteers to actively engage with the ecology of wild bees and wasps, and has often been used in studies with citizen science approaches (Comont and Dickinson 2022; Maher et al. 2019). Some studies have shown that citizen science approaches can suffer from species misidentification and observer biases (Conrad and Hilchey 2011). However, each study and its data quality must be evaluated individually, as approaches involving volunteers often demonstrate good data quality (Kosmala et al. 2016), depending on the approach and data types (Aceves-Bueno et al. 2017; Stevenson et al. 2021). Ideally, sampling methods used in citizen science approaches should ensure both taxonomic accuracy and observer-unbiased data acquisition. A major challenge of citizen science–based monitoring approaches is to obtain sufficient data quality. Therefore, the corresponding sampling methods should be as simple as possible and free from observer bias. One of the sampling methods that has the potential to fulfil these requirements are trap nests. A commonly used trap nest (Staab et al. 2018) consists of natural reeds that need to be cut open to reveal the insects developing in them, which are killed for identification (MacIvor 2017; von Königslöw et al. 2019). An alternative is trap nests made of wooden boards with cavities of pre-defined diameters, covered with transparent plastic films. Theses nests have the potential to offer an observer-unbiased and non-lethal monitoring approach: By unscrewing these trap nests, interested citizens without taxonomic knowledge can take part in monitoring activities, and at the same time, provide photographs of larvae and cocoons. The photographs can be further analysed to collect data on occupation rates, diversity, and development of the taxa. Due to the popularity of insect hotels and to the ability to observe development of the cavity-nesting species throughout the season (Steffan-Dewenter and Schiele 2008; Everaars et al. 2018; Billaud et al. 2021), this method can spur volunteers' interest to get familiar with cavity-nesting Hymenoptera taxa. We henceforth name the trap nests described here as "nesting observation blocks" (NOBs) as they fulfil two functions in a (wooden) *block*: On the one hand, they provide *nesting* sites for cavity-nesting taxa, and on the other, the opportunity to *observe* their development.

Besides raising awareness of the underlying relationship between the abundance and diversity of cavity-nesting Hymenoptera and the surrounding landscape, the use of NOBs enables volunteers to take part in monitoring activities. Using German pollinator monitoring in agricultural landscapes as a case study, we aim to explore whether volunteers who already survey NOBs can also be involved in identifying cavity-nesting taxa of wild bees and wasps. More than 35 species of nest-building wild bees as well as seven cuckoo bee species are known to potentially inhabit trap nests in Germany (Lindermann et al. 2023). Furthermore, around 60 species of aculeate nest-building wasps and their associated parasitoids can be documented with this method. The manageable number of distinguishable taxa of above-ground cavity-nesting

Hymenoptera reduces both the extent and the complexity of identifying them.

Within a conceptualised pollinator monitoring with a citizen science approach, data on cavity-nesting Hymenoptera were collected by volunteers through photographing insect larvae and cocoons in NOBs. Besides involving volunteers in data collection, our aim was to investigate the potential for volunteers to participate in the taxon identification as well. We hypothesised that trained volunteers can correctly identify taxa on family, genus, or species level in the brood cells. We assumed that the success of identification and counting would be affected by specific characteristics of the brood cells, with taxa that have easily distinguishable features being more accurately identified. Additionally, we conducted tests to determine if identification training, provided through educational courses, an illustrated identification key (Lindermann et al. 2023), and an online quiz, enhance the identification skills of volunteers within a season. We also considered the assumption that the prior level of knowledge of the volunteers is negligible for the outcome. The results are discussed in light of integrating volunteers in pollinator monitoring programmes and their potential to enrich our knowledge about cavity-nesting wild bee and wasp species.

METHODS

CITIZEN SCIENCE-BASED POLLINATOR MONITORING IN AGRICULTURAL LANDSCAPES IN GERMANY

In Germany, a pollinator monitoring programme for agricultural landscapes is currently being designed and tested (Thuenen Institute 2023). It follows several aims: Beyond creating a data basis for trend analyses and for estimating the effect of biodiversity enhancement measures, there are modules focusing on the integration of volunteers to raise awareness of the relationship between pollinators and agricultural landscapes. One of these modules focuses on cavity-nesting wild bees and wasps using NOBs. The NOBs in question consist of 25 wooden boards, providing a total of 248 cavities within diameters ranging from 3.2 mm to 9.5 mm (Figure 1*a*). Through this module, we aim to give volunteers, independent of taxonomic knowledge, the opportunity to engage with wild bees and wasps by regularly opening NOBs and documenting their colonization. In a pilot study, volunteers set up a pair of NOBs at predefined sites in agricultural landscapes across Germany. One NOB was set up in March and the other one next to it at the end of May to ensure that species with later activity periods still find cavities to colonise and thus all occurring species can be potentially recorded. The NOBs were opened once per month, in the last ten days of each month, from April to September, to photograph every board (Figure 1*b*). Photographs were taken monthly to collect data not only about occupancy and diversity, but also about phenology of the Hymenoptera species colonising NOBs. To supplement the pilot study, online identification courses and training was offered to volunteers twice a season to promote knowledge and understanding of the cavity-nesting taxa. In the courses, volunteers learned to address the taxon-specific characteristics of the brood cells and completed exercises in which they discussed issues with identification. Additionally, an identification key based on photographs was offered (Lindermann et al. 2023). At the end of the season, volunteers were informed

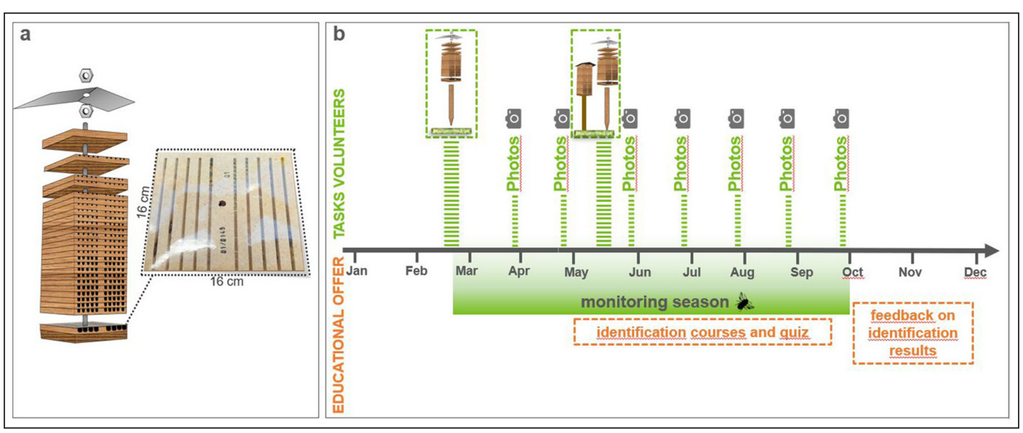

Figure 1 (a) Standardised, nesting observation block (NOB) made of 25 wooden boards and used in the monitoring module of cavity-nesting wild bees in agricultural landscapes. The cavity diameters are arranged in a fixed ratio: seven boards with holes of 3.2 mm diameters, seven boards with 4.8 mm, five boards with 6.4 mm, five boards with 8 mm and one board with 9.5 mm. The boards are 16 × 16 cm in size. To make sure that the brood cells are not disturbed during the data collection, transparent plastic films are ironed onto the boards. An aluminium roof protects against rain. The NOBs are set up at a height of about 1.50 m and are orientated towards the south. **(b)** Schematic workflow of the tasks and education offers for volunteers throughout a monitoring year.

about the taxa that had colonized their NOBs. During the pilot study, the monitoring staff regularly informed the volunteers about the progress and results of the project via a newsletter, and exchanged information with them personally in order to recognise emerging difficulties in advance. This also enabled volunteers to identify with the project. To learn more about the motivation of volunteers to participate and which factors stimulate them to continue contributing to the project, we implemented a feedback survey (Supplemental File 1: Result of the feedback survey). The identity of respondents in the survey was anonymous, so there are no ethical issues about personal identity. As the survey was conducted over the internet and no individual identities were known, we did not need to obtain IRB approval to conduct the online quiz.

IDENTIFICATION OF BROOD CELLS BY VOLUNTEERS

To test whether volunteers can not only provide photographs but also contribute to the taxon identification, we asked volunteers without any taxonomic knowledge to identify colonising taxa of their NOBs at the end of the season (autumn 2021). They identified brood cells of 12,624 cavities of 50 NOBs (Figure 2). The number of identified brood cells per volunteer ranged from 127 to 15,333 and averaged 1,972.5. Based on photographs of the brood cells, it is possible to identify 16 different taxa of wild bees and 15 different taxa of wasps as well as some of their associated parasitoids and predators, to family, subfamily, genus, or even species level (Supplemental File 2: List of cavity-nesting taxa identifiable as larvae). We excluded those taxa from the analysis of which less than ten brood cells were found (n = 35). Moreover, we excluded from the analyses (i) empty cavities (n = 7,830), (ii) unfinished brood cells (n = 533), and (iii) brood cells with dead larvae (n = 23). To model the rate of correct identification by volunteers, we fitted generalised linear mixed-effect models with binomial distribution using Template Model Builder (TMB) with glmmTMB v. 1.1.2.3 (Brooks et al. 2017) and Matrix v. 1.3–4 (Bates and Maechler 2017). Models were fitted in R (R Core Team 2020). We used correct identification (yes /no) as response with the "taxon" identified by experts as explanatory variable. Additionally, we included in the model the variable "presence of larvae," which indicates the presence or absence of a successfully developed larva and cocoon, respectively. Furthermore, we entered the variable "multiple taxa" occurring in one cavity and "volunteers" as random effect in the model.

We fitted the same type of model to predict the rate of correctly counted brood cells (+/– one cell) with the "taxon," the "presence of larvae" and the effect of "multiple taxa" as predictors. We excluded *Osmia brevicornis* Fabricius 1798 and *Megachile* spp., since both taxa do not form clearly definable brood cells, with the exception of *M. ericetorum* Lepeletier 1841 and *M. sculpturalis* Smith 1853. In both models, we tested the knowledge of the volunteers," which was classified based on subjective self-assessment as low (participant felt unsure about identifying the taxa of the NOBs), middle (participant was confident in identifying at least some

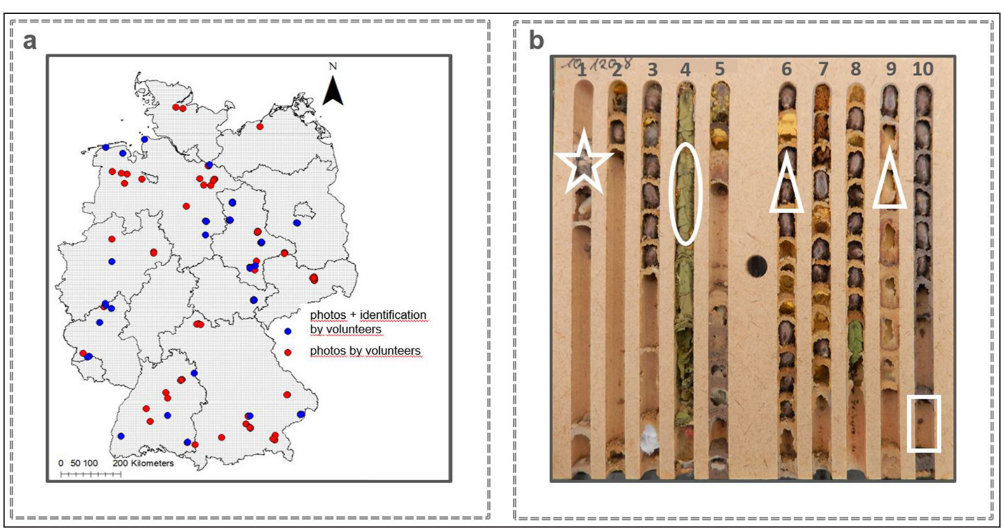

Figure 2 (a) Red points show all sites of nesting observation blocks of the monitoring testing phase in Germany 2021. Volunteers set up nesting observation blocks (NOBs) and photographed them monthly, the identification was done by experts. Blue points show sites of NOBs both photographed and identified by volunteers. The volunteers participated from different regions of Germany. **(b)** The photo of a colonised nesting board illustrates exemplarily the task and challenges of volunteers by identifying the cavity-nesting wild bee and wasp species: Although some larvae and cocoons are easily recognisable (*triangles*), others are more difficult due to infestation of parasitoids (*star*), not clearly separable brood cells (*oval*), or undefinable cells like the empty space between nest closure and first brood cell (= atrium) (*square*).

taxa), and high (participant felt confident in identifying the taxa). As in the previous model, "volunteers" were included as random effect. To test the significances of effects on the model variables, we performed an analysis of deviance with a Type II Wald chi-square test (car v. 3.0–3, Fox et al. 2019) to confirm if the selected variables were significant for the model. After using emmeans v.1.7.2 (Lenth 2021) to calculate the estimated marginal mean values, models were visualised with ggplot2 v. 3.3.5 (Wickham et al. 2016) and multcompView v. 0.1–8 (Graves et al. 2015). The model validation was performed with a 60/40 split, respectively with mlbench v. 2.1–3 (Leisch and Dimitriadou 2010) and caret v. 6.0–90 (Kuhn et al. 2020).

ASSESSMENT OF LEARNING ACHIEVEMENT

An online quiz for the identification of brood cells of the cavity-nesting taxa was also offered. Over a period of eight weeks, ten pictures of brood cells with larvae of cavity-nesting wild bee and wasp species were published weekly on the project website. The participation in the quiz was anonymous. Volunteers were asked to choose a nickname which they used throughout the quiz. The nickname contained information about age and gender of the participants. We asked them to put an "n" at the end of the nickname if the participant had no pre-knowledge or a "y" if they had at least some taxonomic knowledge (e.g., participation in an identification course). The ranges of age, gender, and level of knowledge of the 27 participants are shown in Supplemental File 3: Characteristics of the quiz participants. In the quiz, volunteers were asked to identify cavity-nesting Hymenopteran taxa and count brood cells on ten different photos of a cavity. Volunteers could select the correct answer by a drop-down menu with all NOB taxa that are distinguishable based on photographs. They further typed in the number of nesting cells counted. At the end of each quiz round, the answers were automatically checked for correspondence with the solutions, and volunteers received feedback on their identification results. We modelled the effect on the success rates of identification within the quiz in the same way as described above, using a generalised linear mixed-effect models with TMB with a binomial distribution. To detect change over time, the explanatory variable "week" was included in the model. The "information status" explanatory variable was defined by whether a volunteer had already participated in one of the identification courses offered or otherwise generated knowledge before attempting the online quiz. Furthermore, "age" and "gender" were included as explanatory variables and the nickname as a random factor in the model. It was performed and visualised in the same way as the models of the identification.

RESULTS

IDENTIFICATION SUCCESS OF VOLUNTEERS

During one season, volunteers collected monthly photographs of their NOBs and were educated about cavity-nesting taxa through two identification courses and supporting material. At the end of the season, all individuals had reached the larval stage and were photographed one last time. These photographs were identified by volunteers. The general range in age, gender, and previous experience of the volunteers reflects a cross-section of volunteer characteristics (Supplemental File 4: Characteristics of volunteers involved in taxa identification). Overall, 20 taxa were identified, of which 15 were included in the analysis. Further organisms such as parasitoids and other cavity-nesting insects were noted by the volunteers, but not included in the analysis.

There was a high identification success rate: 92.4% of the taxa in 4,203 analysed cavities were identified correctly by the volunteers, 2.8% were classified as unidentifiable by experts, and 4.8% of the taxa in cavities were incorrectly identified. For model validation, the area under the curve (AUC) amounted to 0.85, providing a good distinctiveness of the predictive classification model (Supplemental File 5: Results of modelling success rate of identification and cell counting). The calculated McFadden's R-squared for model was 0.27, indicating that 27% of the variance was explained by the independent variables in the model. The variable taxon had a highly significant effect on the success rate of identification ($p < 0.001$). Particularly difficult to identify were the brood cells of *Pemphredon* spp. and the subfamily Eumeninae, which had low correct identification rates relative to other taxa in the model results (60.8% and 70.3%, respectively). All other taxa were above a correct identification rate of 85% (Figure 3*a*). Almost every brood cell of the genera *Psenulus* and *Megachile* was correctly identified (99.2% and 99.6%, respectively). The sample size per taxon showed no association with the identification success. In addition, the presence of larvae in the brood cells had a significant positive effect on the identification success ($p < 0.001$). The occupation of multiple taxa in one cavity had a negative effect ($p < 0.001$). The variable "level of knowledge" of the volunteers was not significant ($p = 0.71$) in the Type II Wald chi-square test and was therefore not included in the final model.

Analysing the rate of correct cell counting by trained volunteers, the percentage of correct counting amounted between 59.2% for *Osmia caerulescens* (Linnaeus 1758) and 98% for *Chelostoma florisomne* (Linnaeus 1758), differing between the taxa (Figure 3*b*). The overall success rate was on average 94.4%. The taxon of the cavity to be identified had a significant effect on correct cell counting

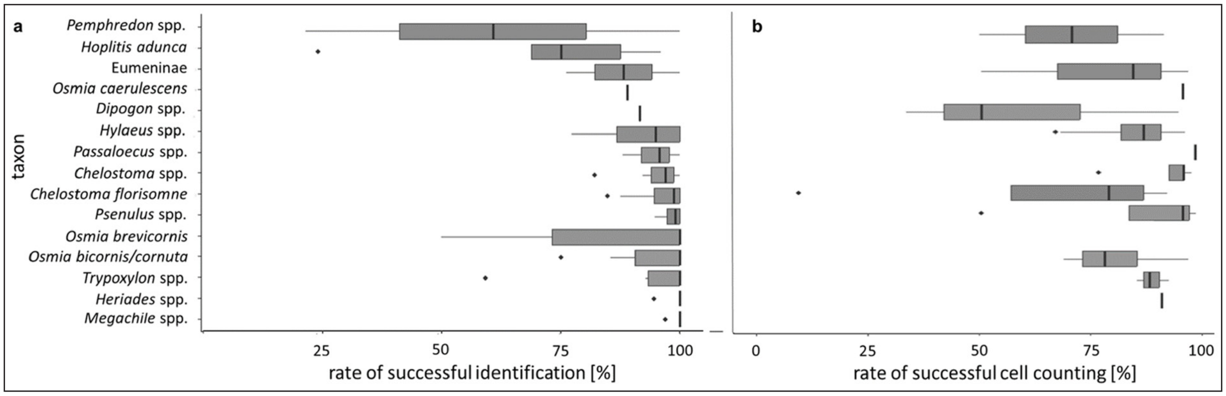

Figure 3 (a) Rate of successful identification per taxon by volunteers. **(b)** Rate of successful cell counting per taxon by volunteers. Data is given on average across volunteers.

(p < 0.001). Multiple taxa in a cavity had a significant negative effect (p = 0.006). The variables "level of knowledge" of the volunteers and "presence of larvae" were not significant (p = 0.05 and p = 0.97) in the Type II Wald chi-square test and were therefore not included in the final model. The calculated McFadden's R-squared for the final model was 0.12 and the AUC amounted to 0.55.

ASSESSMENT OF LEARNING ACHIEVEMENT

To investigate the learning process of the volunteers considering age, gender, and level of knowledge, we fitted a logistic mixed model to predict the success rate of identification. The variables "age" and "gender" were initially included, but then discarded due to no significance in the Type II Wald chi-square test. The model validation yielded 0.72 as value for the AUC, and the calculated McFadden's R-squared for model was 0.11 (Supplemental File 6: Results of modelling success rate of identification in an online quiz). The "time in weeks" showed a significant positive effect on the rate of correct identification (p < 0.001). As the amount of time the quiz was online increased, and as volunteers were able to test their knowledge, the rate of correct identification of the brood cells portrayed in the photographs increased up to week 6 and then remained constant on this level (Figure 4). In addition, participants with pre-knowledge had a significantly higher probability of identifying brood cells correctly (p < 0.001).

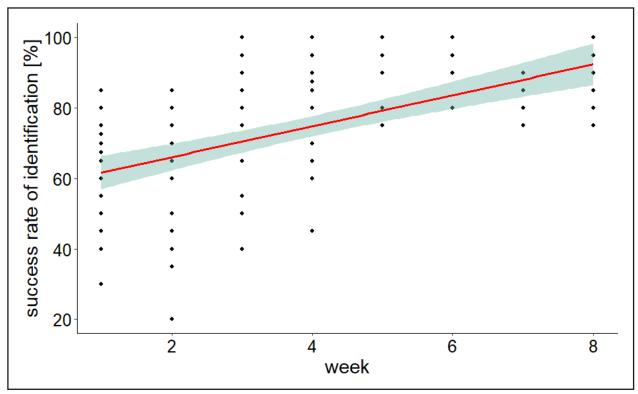

Figure 4 Rate of successful identification of cavity-nesting taxa in the online quiz over time. Over eight weeks, a new quiz task had to be answered every week. The dots show the success rate of identification per quiz participant. With time, successful identification by volunteers increased on average per weekly task.

DISCUSSION

The approach of taking photographs of the NOB boards allowed volunteers without taxonomic knowledge to engage in a monitoring project of cavity-nesting wild bees and wasps. Through the transparent films on top of each NOB board, volunteers had direct insight into the colonisation and development of the immature stages during the season. At the same time, this approach focusing on a manageable number of taxa enables volunteers to identify taxon-specific characteristics. Through identification of aggregated taxa groups, we aimed to familiarize citizens with taxonomic groups and provide them an overview of the taxon diversity of cavity-nesting wild bee and wasp species. Beyond the potential of NOBs for a citizen science–based pollinator monitoring approach, this approach can be supplemented by analysing remaining pollen, faeces, and nesting resources. These remaining substrates can be used for non-lethal species identification through eDNA (Sickel et al. 2023), through food web analysis, and and to determine which of the available resources in the landscape surrounding the NOBs were consumed (Batista Matos et al. 2013, Staab et al. 2018).

SUCCESSFUL IDENTIFICATION BY VOLUNTEERS

We were interested in the question of whether volunteers can be involved in taxon identification of larvae and cocoons.

After one season of offering volunteers identification courses and providing an identification key, 92.4% identification correctness was attained. This result is attributed mainly to the manageable number of taxonomic groups and to identifying taxa on simply visible characteristics such as larvae, cocoons, and shape and material of brood cells. This becomes clear when comparing the results of this study with a citizen science–based study from Italy in which volunteers identified adult wild bees on genus level based on photographs. Just 61.3% of wild bees have been correctly identified (Flaminio et al. 2021). The rate of successful identification in our study was affected mainly by the variable "taxon." This can be attributed to the differently used resources and various ways of building brood cells, but also parasitisation or not fully developed larvae made identification difficult. Moreover, it is possible that those taxa, which occur rather rarely in the NOBs, remain largely unpractised by volunteers, which could decrease identification success. In contrast, more common species offer more repetition during identification, resulting in faster and better identification accuracy (Serret et al. 2019).

We assume that misidentification is attributed to atypical appearance of brood cells, which happens when their typical appearance is changed. The change occurs when females squeeze their brood cells into smaller cavity diameters, which leads to compressed brood cells, which led us to conclude that the appearance of a larva depended on the diameter (Falk et al. 2019). To achieve even better results, we need to improve our identification key with supplementary photographs, in particular, photographs of exceptions such as atypical taxon appearance. We should also spend more time in identification courses on the taxon-specific range of cavity diameters used and how these influence the appearance of the brood cells, clarifying that the model was able to determine relatively validly (AUC) whether the probability of a correct identification was higher or lower based on the influencing variables considered. In the courses, more attention should be drawn to the range of diameters used and how this could affect the appearance illustrated by photographs. This effect was shown in another study of training volunteers in insect identification, in which Perry et al. (2021) found that the correct identification rate of wasps on species level increased with increasing provision of remote identification help and courses. Their correctness amounted to 85% for identifying pictures of wasps and was even higher for identifying the wasps in person. This demonstrates that providing identification courses and guidelines for identification explicitly increases the success rate of identification by volunteers, as it allows interaction between volunteers and the experts (Schmeller et al. 2009).

The identification of immature stages of wild bees and wasps has been comparatively rarely represented in citizen science approaches. However, it offers a good opportunity for volunteers with no taxonomic pre-knowledge to approach the species group and to quickly achieve correct identification results due to manageable number of identifiable taxonomic units, which reduces the error rate of identification. The learning success summarises the benefit of identifying immature stages instead of adult insects, which facilitates wild bee and wasp identification for beginners without overwhelming them. Identifying adult wild bees and wasps in the field is a challenge even for experts, and impossible for the majority of wild bee and wasp species, as inspecting them under binoculars and comparison with reference material is necessary. A citizen science–based study on adult bees showed that volunteers were able to report 48% of morphologically distinct taxa and an additional 8% of bee groups with partial taxonomic resolution that was mostly limited to rough morphological characteristics (Kremen et al. 2011). The species spectrum in our study is smaller and taxonomically diversified (including wasps), so that the characteristics of the brood cells are more distinct. Direct experience with wild bees and wasps and identification training can therefore stimulate interest in taxonomy, increasing the motivation to continue participating in the monitoring and engaging in wild bee and wasp identification (Peter et al. 2021; Santaoja 2022). The high identification accuracy at genus level can stimulate the motivation of volunteers in taking part in monitoring activities. Therefore, the recording methodology of taking photographs of NOB boards is ideally suited for citizen science–based recording and monitoring activities. A further advantage of this approach is that wild bee and wasp individuals do not need to be killed, and no additional optical equipment is necessary.

SUCCESSFUL CELL COUNTING BY VOLUNTEERS

Volunteers were further able to determine occupancy rates of cavity-nesting wild bee and wasp taxa. However, even better results could probably be achieved by offering a more precise definition of brood cells and guidance on how to count them correctly. The importance of precise instructions for inexperienced volunteers has already been shown by other projects on environmental or biodiversity monitoring (Kelling et al. 2019). Our analysis showed that difficulties were often related to the definition of a "complete" cell. In some cases, it seemed not clear for the volunteers whether a started but incomplete cell, a cell with provisions but without a larvae or cocoons, a parasitised cell, or the atrium should also be counted as one single cell. This reinforces the taxon-specific challenges in quantifying brood cells. The presence of unfinished brood cells led to confusion among the volunteers so that these were mostly counted incorrectly. Taxa with clearly recognisable brood cells (and cocoons) and well visible cell demarcations, such as *Osmia bicornis/cornuta*, were counted correctly much more often compared with taxa that use a lot of litter, shavings, or other construction materials and thus make a reliable cell demarcation difficult to observe. This led to lower success rates in cell counting for taxa such as *Pemphredon* spp., due to a dark brown layer covering intermediate walls of this wasp and the variable shades of their larvae (Gathmann and Tscharntke 1999). Nevertheless, due to the low validation accuracy based on AUC, the observed effects of explanatory variables cannot be generalised for correct counting of cells.

SUPPORTIVE ACTIVITIES FOSTER IDENTIFICATION SUCCESS

By training the volunteers with a weekly quiz, the correct identification rate of brood cells in NOBs increased over the time. The analysis has some shortcomings that may have to be considered when interpreting them: While some taxa were mentioned in questions several times, other taxa rarely or never appeared in the quiz and the questions did not increase in difficulty proportionally to the number of participants. Although not all volunteers participated every week, a positive trend can still be observed. Another advantage of a quiz was that the progress of individual volunteers could be monitored (Bonney et al. 2009). To (further) increase the learning success, this tool could be extended with a longer quiz duration, so that insecure volunteers have more time and questions to test, improve, and increase knowledge. In addition, different levels of difficulty could be added, such as parasitisation, to make the quiz attractive to volunteers with different background knowledge and thus be more motivated to participate (Rotman et al. 2014) as gamification increases (Tinati et al. 2017). Attracting new participants who not only show interest in taxonomic identification but who also improve their knowledge and skills about wild bees and wasps in the context of such a project is beneficial and motivating for the volunteers themselves as well as for science (Domroese and Johnson 2017). As a first step, such courses can help to expand taxonomic knowledge and thus counteract the shortage of taxonomists in the long term (Peter et al. 2021). In general, in citizen science–based monitoring programmes in which volunteers are involved in the scientific research can raise the awareness of the importance of species diversity and the underlying relationship between pollinators and the complexity of agricultural landscapes (Toomey and Domroese 2013; Deguines et al. 2020; Meschini et al. 2021). This can often be followed by action (Díaz et al. 2019), such as insect-friendly behaviour.

Consequently, this non-lethal method based on monthly opening of NOBs is suitable for a citizen science–based monitoring approach. In the long term, this method not only allows for tracking the colonisation and development of hymenopteran species throughout the season, but also enables the correlation of changes in phenology and taxa assemblages with changes in climate and land use (e.g., intensification and pesticide applications) (Steffan-Dewenter and Schiele 2008; Peters et al. 2016). In addition, the process of observing and photographing generates an unbiased dataset on a large spatial and temporal scale that enables prediction of long-term trends in cavity-nesting wild bee and wasp populations. At the same time, awareness of insects and their relationships to the surrounding landscape is increasing among participating volunteers. Given the current debates on pollinator protection, it is timely to implement non-lethal sampling methods that lower the inhibition threshold for volunteers to engage in monitoring activities and thus help to increase our knowledge about pollinators.

CONCLUSION

Here, we have shown that standardised NOBs, which can be opened and consist of individual wooden boards, are suitable for a non-lethal and citizen science–based monitoring approach. By photographing the wooden boards, the colonisation and development of cavity-nesting Hymenoptera taxa can be recorded. By implementing the standardised but user-friendly NOB, this approach is applicable for monitoring on a national scale, as the citizen science method was tested using NOBs set up across Germany. Moreover, the results revealed that volunteers can be trained to identify brood cells of cavity-nesting taxa within one season. Consequently, the implementation of the proposed monitoring approach supports raising awareness of volunteers regarding the sensitivity of wild bees and wasps to changes in their habitats and increases volunteer taxonomic knowledge over the long term. Our approach led volunteers to focus on the taxonomic characteristics of wild bees and wasps through a low-threshold introduction into these difficult taxonomic groups, which at the same time are particularly popular among interested people. Finally, the knowledge about these insects strengthens the willingness and efficiency of people to protect them.

DATA ACCESSIBILITY STATEMENT

The analyses supporting the findings of this study are publicly accessible from https://github.com/monagrland/WildBees_CitizenScience.

SUPPLEMENTARY FILES

The Supplementary files for this article can be found as follows:

- **Supplemental File 1.** Result of the feedback survey. DOI: https://doi.org/10.5334/cstp.632.s1
- **Supplemental File 2.** List of cavity-nesting taxa identifiable as larvae. DOI: https://doi.org/10.5334/cstp.632.s2
- **Supplemental File 3.** Characteristics of the quiz participants. DOI: https://doi.org/10.5334/cstp.632.s3
- **Supplemental File 4.** Characteristics of volunteers involved in taxa identification. DOI: https://doi.org/10.5334/cstp.632.s4
- **Supplemental File 5.** Results of modelling success rate of identification and cell counting. DOI: https://doi.org/10.5334/cstp.632.s5
- **Supplemental File 6.** Results of modelling success rate of identification in an online quiz. DOI: https://doi.org/10.5334/cstp.632.s6

ETHICS AND CONSENT

The identity of the respondents was anonymous, so there are no ethical issues about personal identity. As the survey was conducted over the internet and no individual identities are known, we confirm that we did not need to obtain IRB approval to conduct the online quiz.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

Lara Lindermann and Petra Dieker conceptualized the idea and defined the questions and methodological approach. Lara Lindermann carried out the analyses, supported by Swantje Grabener, Niels Hellwig, and Johanna Stahl, and led the writing. All authors contributed to the writing, participated in the discussion, and agreed on the final version of the manuscript.

AUTHOR AFFILIATIONS

Lara Lindermann orcid.org/0000-0002-1387-719X
Thuenen Institute, DE

Swantje Grabener orcid.org/0000-0003-4748-8157
Thuenen Institute, DE

Niels Hellwig orcid.org/0000-0003-4517-1746
Thuenen Institute, Anhalt University of Applied Science, DE

Johanna Stahl
Thuenen Institute, DE

Petra Dieker orcid.org/0000-0003-3468-4810
Thuenen Institute, National Monitoring Centre for Biodiversity, DE

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