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Citizen science versus professional data collection: Comparison of approaches to mosquito monitoring in Germany

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Handling Editor: Yolanda Wiersma**Abstract**

1. Due to the recent emergence of invasive mosquito species and the outbreaks of mosquito-borne diseases in Europe, research on the ecology and diversity of the mosquito fauna has returned to scientific agendas. Through a nationwide surveillance programme in Germany, mosquitoes have been monitored actively by systematically operated traps since 2011, and passively by the 'Mückenatlas' (mosquito atlas) citizen science project launched in 2012.
2. To assess the performance of both monitoring methods we compared the two respective datasets with regard to habitat coverage, species composition and the ability to detect invasive mosquitoes. The datasets include observations from the beginning of the project until the end of 2017.
3. We found significant differences in species composition caused by land use types and the participants' recording activity. Active monitoring performed better in mapping mosquito diversity, whereas passive monitoring better detected invasive species, thereby using data from private premises scientists usually cannot access.
4. *Synthesis and applications.* Active and passive monitoring is complementary. Combining them allows for the determination of mosquito diversity, efficient detection of emerging invasive species and the initiation of rapid-response actions against such invaders. The 'Mückenatlas' sets an example for the usefulness of citizen science when included in a national monitoring programme, an approach that may be worth copying for tackling the global spread of arthropod vectors of disease agents.

KEYWORDS

bias, biodiversity, biological invasions, citizen science, detection, mosquito monitoring, passive surveillance, volunteers

1 | INTRODUCTION

The invasion of non-endemic regions by mosquito vector species is driven by globalization and, in part, climate change and holds serious

implications for human health. For instance, the Asian tiger mosquito *Aedes albopictus*, a species originating from tropical and subtropical regions in Southeast-Asia and the Pacific and an efficient vector of numerous pathogens (Gratz, 2004; Paupy et al., 2009), has been

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spreading on a global scale through the used tire trade, ornamental plant commerce and ground vehicular traffic (Paupy et al., 2009; Scholte & Schaffner, 2007). Due to its ecological plasticity, this species has even invaded temperate zones of Europe and North America, steadily moving northwards (Kraemer et al., 2019). It has been made responsible for repeated disease outbreaks in southern Europe, including dengue and Chikungunya (Gossner et al., 2018). However, many indigenous mosquito species are in principle able to transmit pathogens as well (Kampen & Walther, 2018), often unveiling their health risk only under uncommon environmental conditions, such as *Culex pipiens*, a potential vector of West Nile virus, in Germany.

Reacting to the deficient knowledge about mosquito occurrence and distribution and to the threat mosquitoes can pose to human and animal health, a nationwide monitoring programme was initiated in Germany in 2011. Hence, over the past 8 years, mosquito surveillance has been performed by applying both active and passive approaches. Actively, adult mosquitoes were caught by trapping, netting and aspirating, whereas larvae were collected by dipping (Kampen et al., 2017). In this context, 'passive monitoring' and 'passive surveillance' of mosquitoes refer to approaches where scientists do not actively gather the data themselves, but instead reach out to the public by setting up schemes and programmes, so that citizens can contribute data. One such programme is the citizen science project 'Mückenatlas' which includes citizens in the collection of mosquitoes to complement the active monitoring by scientists (Kampen et al., 2015). It was launched in 2012, at a time when citizen science – the 'active public involvement in scientific research' (Irwin, 2018) – started to gain world-wide momentum.

Citizen science has since supported management decisions and actions of public authorities responding to global challenges and environmental threats (McKinley et al., 2017). Statistical methods have been developed to account for spatio-temporal biases and sampling errors in opportunistic data (Bird et al., 2014; Hochachka et al., 2012; Isaac et al., 2014; van Strien et al., 2013) and doubts on data quality have been rebutted (Danielsen et al., 2014; Lewandowski & Specht, 2015). Public participation has proven especially useful in detecting and managing invasive species (Epps et al., 2014; Hester & Cacho, 2017; Roy et al., 2015), including arthropod vectors of disease agents (Hamer et al., 2018; Porter et al., 2019). In this context, many citizen science projects successfully focus on mosquitoes (e.g. Bazin & Williams, 2018; Jordan et al., 2017; Kampen et al., 2015; Mwangungulu et al., 2016; Palmer et al., 2017; Spence Beaulieu et al., 2019), so that mosquito-related programmes involving the public are being deployed in an increasing number of countries (e.g. Moore et al., 2019; Murindahabi et al., 2018). New projects benefit from the experience of activities already carried out and can accordingly develop tailor-made solutions or build on existing infrastructures [e.g. the adaptation of the 'Mosquito Alert' app in Hongkong (Cheung, 2017) and the 'Mückenatlas' in New Zealand (Museum of New Zealand, 2020) or Globe's Mosquito Mapper Tool (Muñoz et al., 2020)]. Considering the increasing number of projects, an international consortium called 'Global Mosquito Alert' seeks to keep the big picture and provides information and tools for all scales of mosquito surveillance (He & Tyson, 2017; Tyson et al., 2018).

In the case of the 'Mückenatlas', we recorded singular introductions of *Aedes koreicus* and the yellow fever mosquito *Aedes aegypti* and were able to monitor the establishment and spread of the two major invasive species, the Asian bush mosquito *Aedes japonicus* and *A. albopictus* across the country (Kampen & Werner, 2014; Walther & Kampen, 2017). In the event of an invasive vector species record through either active or passive monitoring from locations not considered colonized, the working groups' scientists immediately visit the place of capture to check for local reproduction, evaluate the situation and, depending on the outcome, inform public authorities to consider appropriate measures, for example, control strategies.

Combining professional and citizen science data has recently been proposed for ecological research. For instance, Meentemeyer et al. (2015) predicted a future risk of the Sudden Oak Disease in California based on both data types, and Roy-Dufresne et al. (2019) showed that adding passively collected citizen science data to data generated by scientists improved distribution models of invasive rabbits in Australia. However, comparisons of the quantitative performance of each approach are rare (Goldstein et al., 2014; Palmer et al., 2017), as opposed to the qualitative performance of citizens compared to professional scientists following similar data collection protocols (Paul et al., 2014; van der Velde et al., 2017).

So far, the active and passive monitoring of the German mosquito fauna has been running hand-in-hand for more than 7 years, resulting in an extensive data collection that serve as a basis for valuable insights into the German mosquito fauna. The data have been mainly exploited regarding the detection and distribution of particularly rare species (e.g. Kampen, Schäfer, et al., 2016; Kuhlisch et al., 2019), spreading scenarios (e.g. Kerkow et al., 2019) or population genetics (e.g. Zielke et al., 2015). The data have also been used to inform authorities about the first detection and possible establishment of populations of invasive species to enable them to quickly initiate control measures. No difference has been made between the methodologies underlying the data collection, but mosquito data from both active and passive sources have been pooled. No evaluation of the two collection approaches has yet been carried out, and it has remained unclear which one contributes to which of the monitoring programme's objectives and to what extent.

Here, we quantitatively evaluate the passive and an active monitoring method within the German national mosquito surveillance programme with respect to (a) habitat coverage, (b) species recordings and (c) the ability to detect invasive species. Specifically, we investigate the difference in the proportion and number of land use types in which the mosquitoes were caught to test for completeness of colonizable habitats. We also analyse the spectrum of species recorded by both methods to determine the respective diversity and to find possible causes for differences. Lastly, we evaluate the capability to detect invasive species by assessing whether active or passive monitoring provided more first records of *A. albopictus* and *A. japonicus* of the affected German federal states.

2 | MATERIALS AND METHODS

2.1 | Passive mosquito monitoring by citizens

The 'Mückenatlas' developed 1 year after the official beginning of the nationwide mosquito monitoring programme, at that time rather uninfluenced by the globally emerging citizen science movement. Initially, it was not planned as a citizen science project. This idea evolved as people becoming aware of the trapping activities started to send in mosquitoes; they did so unprompted and out of curiosity. The leading scientists then decided to seize the moment and follow the idea, since then called 'Mückenatlas', by initiating a press release in April 2012, which unexpectedly received a strong response from both regional and national media. Due to the high number of submissions triggered by the news coverage, the 'Mückenatlas' workflow was gradually established as a large-scale citizen science project.

Participation in the project is very simple and requires no particular knowledge, training or protocol. People are asked to collect mosquitoes wherever and whenever they want to, with the only prerequisite that the insects remain physically intact, for example, are not smashed but caught alive, if possible, using a closeable container. To kill a caught mosquito, it is recommended to put the sample into the freezer for 24 hr. In addition, the participants are asked to fill a submission form, which they can download from the website www.mueckenatlas.com, with information about the catch (most importantly, time and place). If internet is not available, submission forms can be sent in paper form to the participants. Hence, the project design also allows individuals to participate who are not comfortable with using digital tools, such as smartphone apps, or do not have web access at all. As a final step, the citizen scientists send the sample and the submission form at their own expense to the project's designated post office box. Only in a few cases they do not frank their packages, so that the postage costs must be paid from the project budget. For general requests about participation or other questions, a video explanation and FAQs on the website are offered; participants and other interested groups can also make contact online.

After identification, each participant receives a personal e-mail or letter from the project team, which is demonstrably one of the most important but also most time-consuming factors for the success of the 'Mückenatlas'. In this reply, the participant receives information about the species caught and also tips on how to eliminate and prevent mosquito nuisance. Even if the entry contained another taxon or the mosquito was in a condition that it could not be identified, a response is given. In addition, every participant is offered the possibility to have their name or a pseudonym marked on the website's 'collectors' map'. Research results based on their data are regularly communicated via the website after publication. Potential participants are not specifically recruited but continuously addressed via the mass media (e.g. by issuing press releases) and, to a small extent, via social media and on the occasion of public events to draw attention to the project. Our good relations with media editors, which have developed over the years, as well as the fact that (invasive) mosquito species and the associated health risks are relevant and reportable topics help in this respect.

In general, participants submit one to five mosquitoes in a sample, most of which are in an identifiable state. In rare cases, participants operating own industrial mosquito traps send hundreds of specimens, mostly of the same species. To ensure data quality, species identification is only carried out by experienced experts of the working group. Severely damaged specimens that cannot be identified to species level morphologically are determined genetically (Heym et al., 2018; Werner et al., 2020). By June 2020, over 25,500 citizens have participated and submitted a total of about 138,000 mosquitoes.

2.2 | Active mosquito monitoring by scientists

Active mosquito monitoring was done by trapping with BG-Sentinel traps (Biogents) equipped with gas bottles releasing CO₂ as attractant. This type of trap has proven to be more efficient and to attract a wider range of species than other trap types commonly used for collecting mosquitoes (e.g. Lühken et al., 2014). As opposed to the citizen science data, the data collected by the BG-Sentinels are standardized and allow analyses beyond the phenology and distribution of mosquitoes, such as assessing species abundances.

From 2011 to 2014, 68 traps were distributed all over Germany, placed deliberately in wetlands, urban surroundings, zoological gardens, cemeteries, airports and highway service stations. In the years 2015 to 2017, trapping followed a distribution regime: 64 traps were run annually only in the eastern half of Germany, while the western half was sampled by other groups. In that period, traps were randomly placed in a grid cell raster in near-natural, rural and urban settings, which were selected by a computer algorithm according to the percentage of these landscape structures occurring in Germany. All traps were run once per week for 24 hr from April to October, resulting in some 130,000 caught mosquito specimens.

2.3 | Datasets and statistical analyses

Trapped and submitted mosquitoes were identified morphologically under the microscope, using a determination key (Becker et al., 2010), or genetically in the case of severely damaged specimens or complex species (Heym et al., 2018; Werner et al., 2020). Information about the catches of both methods is entered into the German mosquito database CULBASE. For each species submitted to the 'Mückenatlas' or caught in one 24-hr trapping cycle, a single CULBASE entry is generated, hereafter indicated as 'observation', regardless of the corresponding specimen count that is recorded as separate covariate. We exported datasets for active and passive monitoring for the years 2011 to 2017 and 2012 to 2017, respectively, and only used observations for comparison, disregarding the number of specimens per species and observation. All analyses were performed with the same set of covariates for both datasets (see Table S1). Mosquito groups or complexes were considered as a whole to account for impossibilities or uncertainties in differentiating females between species (see Table S2). For simplification, though, we refer to these complexes or groups as 'species'. The database automatically generates

land use type based on CORINE Land Cover data level 3, which we manually re-classified to level 2 in order to improve presentation clarity. CORINE Land Cover data showed an accuracy of 82.8% for Germany in blind interpretation in 2012 (EU, 2012). Explorative and descriptive statistical analysis featuring frequency tables, (heat)maps, species accumulation curves, Fisher's exact test and Bray Curtis dissimilarity were conducted in R version 3.5.2 (R Core Team, 2018), deploying the packages SUMMARYTOOLS (Comtois, 2019), RGDAL (Bivand et al., 2019), VEGAN (Oksanen et al., 2019), VIRIDIS (Ganier, 2018) and GGLOT2 (Wickham, 2016).

3 | RESULTS

3.1 | Habitat coverage

The 'Mückenatlas' dataset geo-locations ($n = 11,277$) exceed by far the number of trapping sites ($n = 258$, Figure 1a). Therefore, we consolidated geo-locations per municipality, resulting in 221 municipalities (0.02% of all German municipalities as of 2017) covered by active monitoring and 3,221 municipalities (29.1%) covered by passive monitoring, with an average of 52.8 and 6.8 observations per municipality, respectively. The land use types incorporated by 'Mückenatlas' data ($n = 14$) are disproportionate because nearly two thirds (65.3%) of the submissions came from artificial surfaces, particularly urban fabric, green urban areas or sports and leisure facilities. The land use types ($n = 13$) displayed in the trapping approach are less biased, with 47.8% agricultural areas, 28.0% natural areas and 17.9% artificial surfaces, thus approximately representing the actual proportion of the German-wide land use distribution (Figure 1b, see Table S3).

3.2 | Species recordings and composition

According to our species categorization, the 'Mückenatlas' recorded 36 mosquito species, while 38 species were trapped with BG-Sentinel. Active monitoring needed far less municipalities than passive monitoring to collect all recorded species (Figure 2a). For the latter, it took more

than 3,000 communities to reach the total number of species, although half of them ($n = 18$) were already detected after submissions from 57 municipalities (active: $n = 19$, needing 29 municipalities). The rates of the species' first records over time, as shown by the species discovery curves (Figure 2b), are comparable between the two approaches despite the earlier start and the slightly higher species richness of active monitoring.

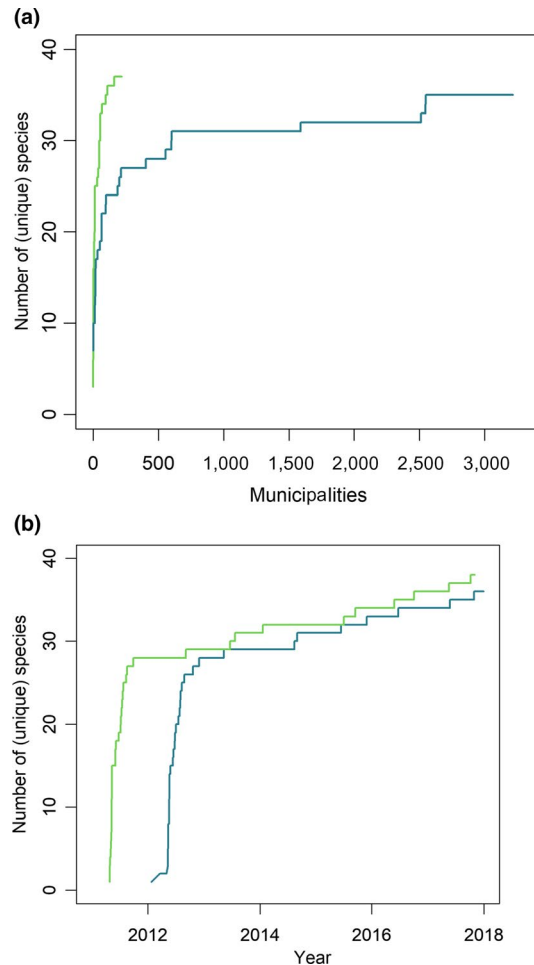


FIGURE 2 Species collectors curve, (a) over sites (municipalities), and (b) over time of active (green) and passive (blue) monitoring

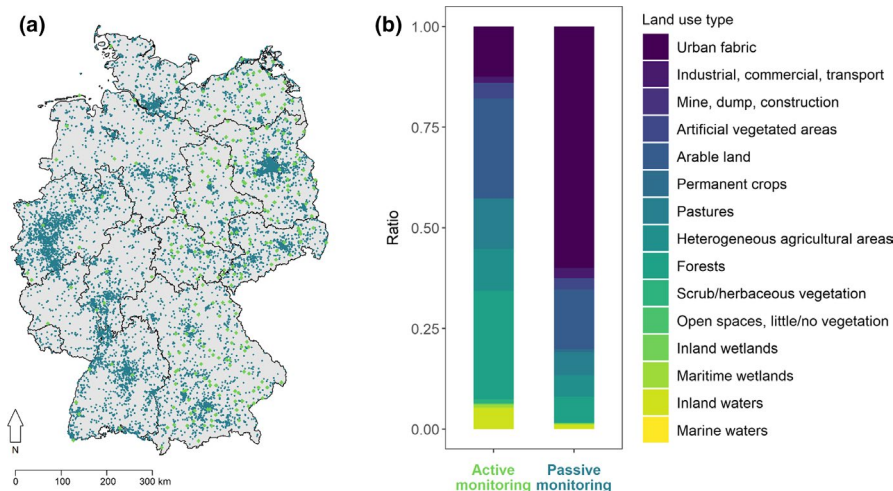


FIGURE 1 (a) Locations of BG-Sentinel traps (active monitoring: green points) and of 'Mückenatlas' submissions by citizen scientists (passive monitoring: blue points). (b) Land use type proportions of catch locations in active and passive monitoring datasets, broken down to CORINE level 2

Both curves show an asymptotic development after recording 28 species within a year after each project start (27 September 2011 for active, 30 November 2012 for passive monitoring). Then it took both methods more than 5 years to collect the number of species reached by the end of 2017.

The active and passive monitoring datasets share 72.3% of the species collected (Bray–Curtis Index = 0.36), however, with a

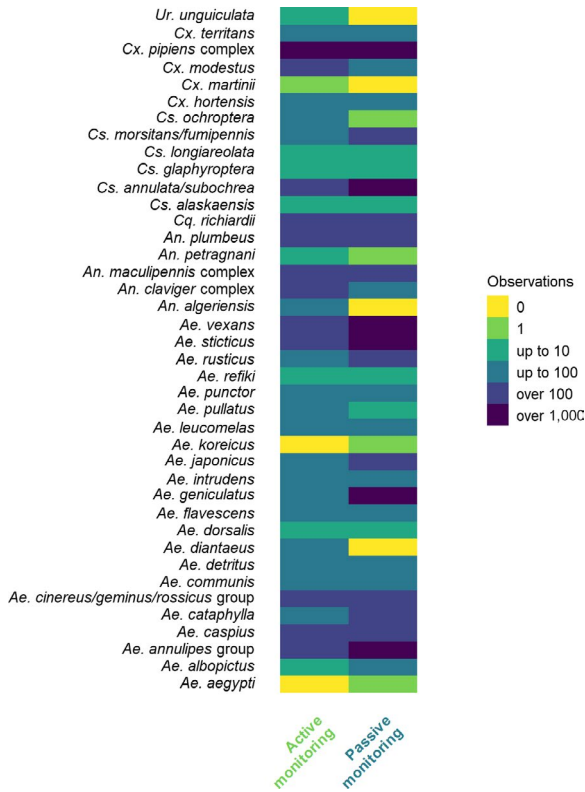


FIGURE 3 Species heat map of active and passive monitoring, showing the number of collected species by categories. *Species allocation: *Culex pipiens* complex: *Culex pipiens* including biotypes *pipiens* and *molestus*, *Culex torrentium*; *Aedes annulipes* group: *Aedes annulipes*, *Aedes cantans*, *Aedes excrucians*, *Aedes riparius*; *Anopheles maculipennis* complex: *Anopheles atroparvus*, *Anopheles daciae*, *Anopheles maculipennis*, *Anopheles messeae*. Furthermore combined to account for impossibilities or uncertainties in differentiating females between species: *Aedes cinereus/geminus/rossicus* group, *Culiseta annulata/subochrea*, *Culiseta morsitans/fumipennis*

significant difference in species composition ($p < 0.001$, Fisher's exact test; Figure 3). The *Culex pipiens* complex was the most commonly recorded taxon for both methods, but it was far more often actively trapped ($n = 5,847$, 50.8%) than passively submitted ($n = 8,382$, 38.7%). Remarkably, the 'Mückenatlas' frequently registered *Culiseta annulata*, the only other species with a share over 10% ($n = 3,790$, 17.5%; see Table S2 for complete species lists and exact observation numbers). We recorded notably more *Aedes geniculatus* (6.2% vs. 0.6%) and *A. japonicus* (4.1% vs. 0.3%) in the 'Mückenatlas' than via active monitoring. Some species were found by one approach only, but both monitoring methods combined detected the currently assumed entire mosquito diversity of 52 species in Germany.

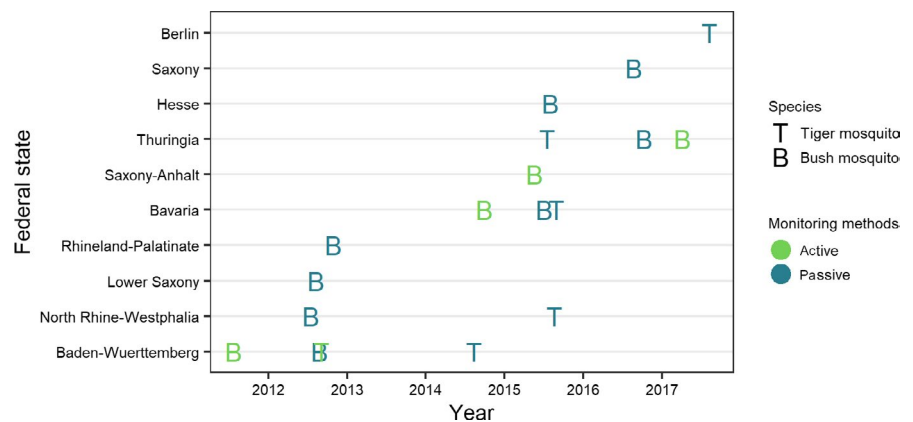
3.3 | Invasive species

Both methods detected *A. japonicus*, *A. albopictus*, *Aedes petragrani* and *Culiseta longiareolata*, but the 'Mückenatlas' additionally reported single specimens of *A. koreicus* and *A. aegypti*. First records of the most widespread *A. albopictus* and *A. japonicus* were made by the 'Mückenatlas' in more federal states ($n = 10$) than by active monitoring ($n = 4$; Figure 4).

4 | DISCUSSION

The 'Mückenatlas' is a rather unique approach among the long-term citizen science mosquito monitoring programmes worldwide. First, it works completely analogue without an app or another e-entomology method. Internet access is not even necessary for participants, although visiting the project's website improves the participants' experience and background knowledge. Second, as the focus of the project lies on compressing the geographic coverage by increasing the number of unique collection locations, any equipment, catch specifications or protocols are waived in favour of a low-threshold for participation. Third, communication is realized personally with each and every participant, which is a key element of the project. Although the cost-effectiveness

FIGURE 4 First records of *Aedes albopictus* (T; Asian tiger mosquito) and *Aedes japonicus* (B; Asian bush mosquito) in German federal states by active (green) and passive (blue) monitoring



of this citizen science programme has not yet been accurately quantified in comparison to active monitoring, as done in other projects (Braz Sousa et al., 2020; Goldstein et al., 2014; Palmer et al., 2017), most of the costs of the programme are incurred by the project's staff salaries, very little by recruiting participants through public events and media relations, and almost none by the citizens' data collection.

With submissions from over 11,000 unique geo-locations and more than 3,000 municipalities, the 'Mückenatlas' achieves a broad spatial coverage, demonstrating a major benefit of citizen science (Dickinson et al., 2010; Irwin, 2018). The lower quantity of municipalities covered by active monitoring better reflects the typical proportion of land use types in Germany, and therefore, we consider the resulting active monitoring dataset representative and able to detect the entire mosquito diversity in Germany, even if most traps included in this study were placed in geographically eastern Germany. By contrast, the 'Mückenatlas' submissions indeed originated from more land use types, but display an overrepresentation of urban areas, as most of the catch locations were based in or around people's homes, in houses, apartments and gardens. An advantage is, however, that we receive data from private properties in this way that scientists normally cannot access (Dickinson et al., 2010; Epps et al., 2014). Such data are urgently needed to assess the impact of urban development on ecosystem functioning and biodiversity (Dunn & Beasley, 2016; Spear et al., 2017).

The higher species richness yielded by active monitoring is presumably caused by the selective placement of traps (e.g. in swamps, on floodplains or peatlands) in the 2011–2014 period. The lower species richness of the passive monitoring might be due to the overrepresentation of urban areas. Considering the time needed to collect the respective number of species, both monitoring methods are comparable as shown by the species discovery curves. For both methods, the most recent 10 first records of species constituted of invasive or very rare taxa, suggesting that chances to detect either of them appear to be equally low for active and passive monitoring.

To simplify the comparison of species recordings, we have assigned the mosquito species to the corresponding groups and complexes. However, when analysing the data in an entomological-medical context, it is essential to consider differences in the ecological traits of the individual taxa, such as within the *Culex pipiens* complex. Both monitoring methods differed significantly in species composition, and surprisingly also in the most frequently recorded species. Although *C. annulata* and *A. geniculatus* are geographically widespread species, they were considerably less frequently collected by active monitoring than by passive monitoring. Reasons for the high submission numbers to the 'Mückenatlas' compared to active trapping are probably the morphological appearances of both species. The ringed legs of *C. annulata* and the black-and-white habitus of *A. geniculatus* match the characteristics described by the media when featuring the invasive *A. albopictus* or *A. japonicus*. In addition, *C. annulata* and *A. geniculatus* are fairly

large-sized mosquitoes, and communication with submitters to the 'Mückenatlas' has shown that invasive species are generally thought to be extraordinarily big, not least owing to the name affix 'tiger'. This substantiates our suspicion that participants actively look out for, or only become active when they think to have recognized invasive species, creating a recording bias known from other studies (Roy et al., 2015; Vaux & Medlock, 2015). The same effect probably causes the higher number of registrations of the actually invasive *A. japonicus* in the 'Mückenatlas', although experience shows that this species is not readily collected by the BG-Sentinel trap (pers obs.).

In the case of *C. annulata*, the difference in seasonality of both monitoring methods affects the number of observations as well. *Culiseta annulata* often overwinters in basements of, or fire wood stacks near, houses and is continuously submitted to the 'Mückenatlas' during the winter months and early spring, whereas the BG-Sentinel traps were solely operated from April through October, missing the chance to catch overwintering specimens.

Among the six species not shared between the two approaches, two invasive mosquitoes were only detected by the 'Mückenatlas', *A. koreicus* and *A. aegypti*. The latter species was recorded once, and it became clear after inspection of the submitter's home that the species had been passively displaced by travelling. Eggs of this species, apparently attached to imported exotic plants, hatched under the warm indoor conditions in the water bowls, in which the plants were placed, resulting in an indoor mosquito population. The respective participants explained they were worried about Zika virus transmission and hence submitted the species to the citizen science project (Kampen, Jansen, et al., 2016). Species only found by active monitoring (*Anopheles algeriensis*, *Aedes diaantaeus*, *Culex martinii* and *Uranotaenia unguiculata*) are either rare, bound to specific habitats outside urban areas, exophilic or do not feed on humans (Becker et al., 2010). The rediscovery of *A. algeriensis* and *C. martinii* (Kuhlisch et al., 2018b; Tippelt et al., 2018) by BG-Sentinel trapping highlights the suitability of the active surveillance method for recording the entire mosquito diversity.

Our prior analysis of invasive species is constrained by the unequal number of sites sampled in the respective federal states and the possibility of first detections of new mosquito species by project partners based on data not yet released. Concerning Figure 4, we neither found any published data nor heard from colleagues on earlier first records of *A. japonicus* or *A. albopictus* in hitherto unpopulated federal states after 2011 and therefore can conclude that both invasive species are predominantly detected by the 'Mückenatlas'. This citizen science project has thus become an invaluable tool for surveying invasive mosquitoes, corroborating recent findings of the usefulness of passive surveillance for dealing with biological invasions (Hester & Cacho, 2017; Sladonja & Poljuha, 2018). As a practical example of management implications and the interplay of both monitoring methods, the city of Erding in Bavaria initiated eradication measurements in a cemetery after sampling provided evidence of local reproduction. In another case, the 'Mückenatlas' submission

of the first *A. albopictus* from Thuringia (Jena) led to 3 years of active monitoring tracking established populations in different cemeteries (Kuhlish et al., 2018a).

5 | CONCLUSIONS

In this study, we compared active (via BG-Sentinel traps) with passive (via a citizen science project) mosquito monitoring efforts over a time period of 7 years. Our analyses revealed that passive monitoring is an efficient way to collect species data in direct proximity to humans and their surrounding environments, reducing volunteer management and equipment costs, and empowering citizens to provide important information that benefits both society and science. Passive monitoring performed better in detecting invasive species, because citizen scientists predominantly sampled in urban areas where most invaders arrive with introduction vehicles, but also due to increased alertness towards the perils of *A. japonicus* and *A. albopictus* resulting from massive German media coverage. This sampling bias of citizen scientists is mitigated by active monitoring, which performs notably better in capturing the entire mosquito diversity through selective placement of traps. In addition, trapping appears to be especially useful to validate first detections as well as estimate infestations with subsequent, methodically conducted surveillance.

With these project-specific advantages, the 'Mückenatlas' proved to be a valuable tool to obtain an increasingly accurate picture of the occurrence and distribution of mosquitoes over a long period of time, including the spread and detection of invasive species. Its project design could serve as an example for other citizen science programmes to complement or substitute active approaches aiming at (a) large-scale, long-term surveillance, (b) detecting invasive or rare species and (c) a comprehensive recording of (mosquito) biodiversity in urban settings. As opposed to that, we think that the 'Mückenatlas' approach is less suitable for studying specific species over a short time period, for spatially limited regions or selected habitat types (except for indoor diversity) and for investigations bound to certain times, that is, when randomness and loss of control is not acceptable. In these cases, apps like 'Mosquito Alert' (Palmer et al., 2017), traps run by citizens (Johnson et al., 2018) or a strict protocol followed by a designated stakeholder group (Tarter et al., 2019) might be more appropriate.

While the citizen science programme has been running successfully in Germany since 2012, its design might face difficulties in other countries due to cultural, economic and social differences. People might not be willing or able to cover postal costs, especially in socio-economically weak countries, which are particularly threatened by mosquito-borne diseases. Moreover, attitudes towards science might not be positive enough, the health concern or the interest in the living environment not strong enough to justify sufficient time investment. Therefore, we recommend prior proof-of-concept studies to test a project's design, workflow and acceptance, as carried out by Braz Sousa et al. (2020), also to create a solid basis for grant applications.

Momentum is there to encourage local and national authorities to trust the solid evidence that formal surveillance programmes could benefit from a citizen science component. Especially to achieve the goals of Integrated Vector Management as defined by the WHO – such as cost-efficiency, sustainability, precise knowledge on distribution and empowerment of communities – the involvement of citizen science can play an increasingly important role in the future (Fernandes et al., 2018; Fouet & Kamdem, 2019). However, it must be clear that citizen science cannot be the one-fits-all solution, but only one tool in the toolbox of mosquito surveillance.

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AUTHORS' CONTRIBUTIONS

N.P., H.K. and D.W. devised the main conceptual idea; N.P. planned and performed the data analysis; H.K. and D.W. provided the mosquito data and supervised the project; N.P. led the writing of the manuscript with much input from H.K., J.M.J. and D.W. All authors contributed critically to the drafts.

DATA AVAILABILITY STATEMENT

An anonymised version of the data without geo-coordinates of the trap and catch locations is available via the Open Research Data repository at the Leibniz-Centre for Agricultural Landscape Research (ZALF), Germany, <https://www.doi.org/10.4228/ZALF.DK.151> (Pernat et al., 2020). Sharing the raw data including the exact geo-coordinates would violate the personal privacy of the citizen scientists.

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REFERENCES

- Bazin, M., & Williams, C. R. (2018). Mosquito traps for urban surveillance: Collection efficacy and potential for use by citizen scientists. *Journal of Vector Ecology*, 43, 98–103. <https://doi.org/10.1111/jvec.12288>
- Becker, N., Petric, D., Zgomba, M., Boase, C., Madon, M. B., Dahl, C., & Kaiser, A. (2010). *Mosquitoes and their control* (2nd ed.). Springer. <https://doi.org/10.1007/978-3-540-92874-4>

- Bird, T. J., Bates, A. E., Lefcheck, J. S., Hill, N. A., Thomson, R. J., Edgar, G. J., Stuart-Smith, R. D., Wotherspoon, S., Krkosek, M., Stuart-Smith, J. F., Pecl, G. T., Barrett, N., & Frusher, S. (2014). Statistical solutions for error and bias in global citizen science datasets. *Biological Conservation*, 173, 144–154. <https://doi.org/10.1016/j.biocon.2013.07.037>
- Bivand, R., Keitt, T., & Rowlingson, B. (2019). *rgdal: Bindings for the 'Geospatial' data abstraction library*. R package version 1.4-3. Retrieved from <https://CRAN.R-project.org/package=rgdal>
- Braz Sousa, L., Fricker, S. R., Doherty, S. S., Webb, C. E., Baldock, K. L., & Williams, C. R. (2020). Citizen science and smartphone e-entomology enables low-cost upscaling of mosquito surveillance. *Science of the Total Environment*, 704, 1–10. <https://doi.org/10.1016/j.scitoenv.2019.135349>
- Cheung, R. (2017). *Hong Kong citizen scientists localise mosquito tracking app to let people report sightings of the disease carriers*. South China Morning Post, 30 May 2017. Retrieved from <https://www.scmp.com/lifestyle/health-beauty/article/2095777/hong-kong-citizen-scientists-localise-mosquito-tracking-app>
- Comtois, D. (2019). *summarytools: Tools to quickly and neatly summarize data*. R package version 0.9.3. Retrieved from <https://CRAN.R-project.org/package=summarytools>
- Danielsen, F., Jensen, P. M., Burgess, N. D., Altamirano, R., Alviola, P. A., Andrianandrasana, H., Brashares, J. S., Burton, A. C., Coronado, I., Corpuz, N., Enghoff, M., Fjeldsø, J., Funder, M., Holt, S., Hübertz, H., Jensen, A. E., Lewis, R., Massao, J., Mendoza, M. M., ... Young, R. (2014). A multicountry assessment of tropical resource monitoring by local communities. *BioScience*, 64, 236–251. <https://doi.org/10.1093/biosci/biu001>
- Dickinson, J. L., Zuckerberg, B., & Bonter, D. N. (2010). Citizen science as an ecological research tool: Challenges and benefits. *Annual Review of Ecology, Evolution, and Systematics*, 41, 149–172. <https://doi.org/10.1146/annurev-ecolsys-102209-144636>
- Dunn, R. R., & Beasley, D. E. (2016). Democratizing evolutionary biology, lessons from insects. *Current Opinion in Insect Science*, 18, 89–92. <https://doi.org/10.1146/annurev-ecolsys-102209-144636>
- Epps, M. J., Menninger, H. L., LaSala, N., & Dunn, R. R. (2014). Too big to be noticed: Cryptic invasion of Asian camel crickets in North American houses. *PeerJ*, 2, 1–15. <https://doi.org/10.7717/peerj.523>
- European Union (EU). (2012). Copernicus Land Monitoring Service 2012, European Environment Agency (EEA).
- Fernandes, J. N., Moise, I. K., Maranto, G. L., & Beier, J. C. (2018). Revamping mosquito-borne disease control to tackle future threats. *Trends in Parasitology*, 34, 359–368. <https://doi.org/10.1016/j.pt.2018.01.005>
- Fouet, C., & Kamdem, C. (2019). Integrated mosquito management: Is precision control a luxury or necessity? *Trends in Parasitology*, 35, 85–95. <https://doi.org/10.1016/j.pt.2018.10.004>
- Ganier, S. (2018). *viridis: Default color maps from 'matplotlib'*. R package version 0.5.1. Retrieved from <https://CRAN.R-project.org/package=viridis>
- Goldstein, E. A., Lawton, C., Sheehy, E., & Butler, F. (2014). Locating species range frontiers: A cost and efficiency comparison of citizen science and hair-tube survey methods for use in tracking an invasive squirrel. *Wildlife Research*, 41, 64–75. <https://doi.org/10.1071/WR13197>
- Gossner, C. M., Ducheyne, E., & Schaffner, F. (2018). Increased risk for autochthonous vector-borne infections transmitted by *Aedes albopictus* in continental Europe. *EuroSurveillance*, 23, 1–6. <https://doi.org/10.2807/1560-7917.ES.2018.23.24.1800268>
- Gratz, N. G. (2004). Critical review of the vector status of *Aedes albopictus*. *Medical and Veterinary Entomology*, 18, 215–227. <https://doi.org/10.1111/j.0269-283X.2004.00513.x>
- Hamer, S. A., Curtis-Robles, R., & Hamer, G. L. (2018). Contributions of citizen scientists to arthropod vector data in the age of digital epidemiology. *Current Opinion in Insect Science*, 28, 98–104. <https://doi.org/10.1016/j.cois.2018.05.005>
- He, Y., & Tyson, E. (2017). *Survey results: Complexities & overlaps in existing citizen science mosquito projects*. Woodrow Wilson International Center for Scholars.
- Hester, S. M., & Cacho, O. J. (2017). The contribution of passive surveillance to invasive species management. *Biological Invasions*, 19, 737–748. <https://doi.org/10.1007/s10530-016-1362-4>
- Heym, E. C., Kampen, H., & Walther, D. (2018). Mosquito species composition and phenology (Diptera, Culicidae) in two German zoological gardens imply different risks of mosquito-borne pathogen transmission. *Journal of Vector Ecology*, 43, 80–88. <https://doi.org/10.1111/jvec.12286>
- Hochachka, W. M., Fink, D., Hutchinson, R. A., Sheldon, D., Wong, W. K., & Kelling, S. (2012). Data-intensive science applied to broad-scale citizen science. *Trends in Ecology & Evolution*, 27, 130–137. <https://doi.org/10.1016/j.tree.2011.11.006>
- Irwin, A. (2018). Citizen science comes of age. *Nature*, 562, 480–482.
- Isaac, N. J. B., van Strien, A. J., August, T. A., de Zeeuw, M. P., Roy, D. B., & Anderson, B. (2014). Statistics for citizen science: Extracting signals of change from noisy ecological data. *Methods in Ecology and Evolution*, 5, 1052–1060. <https://doi.org/10.1111/2041-210x.12254>
- Johnson, B. J., Brosch, D., Christiansen, A., Wells, E. D., Wells, M., Bhandoola, A. F., Milne, A., Garrison, S., & Fonseca, D. M. (2018). Neighbors help neighbors control urban mosquitoes. *Scientific Reports*, 8, 1–6. <https://doi.org/10.1038/s41598-018-34161-9>
- Jordan, R. C., Sorensen, A. E., & Ladeau, S. (2017). Citizen science as a tool for mosquito control. *Journal of the American Mosquito Control Association*, 33, 241–245. <https://doi.org/10.2987/17-6644R.1>
- Kampen, H., Jansen, S., Schmidt-Chanasit, J., & Walther, D. (2016). Indoor development of *Aedes aegypti* in Germany, 2016. *EuroSurveillance*, 21, 1–3. <https://doi.org/10.2807/1560-7917.ES.2016.21.47.30407>
- Kampen, H., Medlock, J. M., Vaux, A., Koenraadt, C., van Vliet, A., Bartumeus, F., Oltra, A., Sousa, C. A., Chouin, S., & Werner, D. (2015). Approaches to passive mosquito surveillance in the EU. *Parasites & Vectors*, 8(9), 1–13. <https://doi.org/10.1186/s13071-014-0604-5>
- Kampen, H., Schäfer, M., Zielke, D. E., & Walther, D. (2016). The *Anopheles maculipennis* complex (Diptera: Culicidae) in Germany: An update following recent monitoring activities. *Parasitology Research*, 115, 3281–3294. <https://doi.org/10.1007/s00436-016-5189-9>
- Kampen, H., Schuhbauer, A., & Walther, D. (2017). Emerging mosquito species in Germany – A synopsis after 6 years of mosquito monitoring (2011–2016). *Parasitology Research*, 116, 3253–3263. <https://doi.org/10.1007/s00436-016-5189-9>
- Kampen, H., & Walther, D. (2018). Vector potential of mosquito species (Diptera: Culicidae) occurring in Central Europe. In G. Benelli & H. Mehlhorn (Eds.), *Mosquito-borne diseases: implications for public health. Parasitology research monographs* (Vol. 10, pp. 41–68). https://doi.org/10.1007/978-3-319-94075-5_5
- Kampen, H., & Werner, D. (2014). Out of the bush: The Asian bush mosquito *Aedes japonicus japonicus* (Theobald, 1901) (Diptera, Culicidae) becomes invasive. *Parasites & Vectors*, 7(1), 1–10. <https://doi.org/10.1186/1756-3305-7-59>
- Kerkow, A., Wieland, R., Koban, M. B., Hölker, F., Jeschke, J. M., Werner, D., & Kampen, H. (2019). What makes the Asian bush mosquito *Aedes japonicus japonicus* feel comfortable in Germany? A fuzzy modelling approach. *Parasites & Vectors*, 12(1), 1–17. <https://doi.org/10.1186/s13071-019-3368-0>
- Kraemer, M. U. G., Reiner, R. C., Brady, O. J., Messina, J. P., Gilbert, M., Pigott, D. M., Yi, D., Johnson, K., Earl, L., Marczak, L. B., Shirude, S., Davis Weaver, N., Bisanzio, D., Perkins, T. A., Lai, S., Lu, X., Jones, P.,

- Coelho, G. E., Carvalho, R. G., ... Golding, N. (2019). Past and future spread of the arbovirus vectors *Aedes aegypti* and *Aedes albopictus*. *Nature Microbiology*, 4, 854–863. <https://doi.org/10.1038/s41564-019-0376-y>
- Kuhlisch, C., Kampen, H., & Walther, D. (2018a). The Asian tiger mosquito *Aedes albopictus* (Diptera: Culicidae) in Central Germany: Surveillance in its northernmost distribution area. *Acta Tropica*, 188, 78–85. <https://doi.org/10.1016/j.actatropica.2018.08.019>
- Kuhlisch, C., Kampen, H., & Walther, D. (2018b). Rediscovery of *Culex (Neoculex) martinii* Medschid, 1930 (Diptera, Culicidae) in Germany. *Parasitology Research*, 117, 3351–3354. <https://doi.org/10.1007/s00436-018-6056-7>
- Kuhlisch, C., Kampen, H., & Werner, D. (2019). On the distribution and ecology of *Culiseta (Culicella) ochroptera* (Peus) (Diptera: Culicidae) in Germany. *Zootaxa*, 4576, 544–558. <https://doi.org/10.11646/zootaxa.4576.3.7>
- Lewandowski, E., & Specht, H. (2015). Influence of volunteer and project characteristics on data quality of biological surveys. *Conservation Biology*, 29, 713–723. <https://doi.org/10.1111/cobi.12481>
- Lühken, R., Pfitzner, W., Börstler, J., Garms, R., Huber, K., Schork, N., Steinke, S., Kiel, E., Becker, N., Tannich, E., & Krüger, A. (2014). Field evaluation of four widely used mosquito traps in Central Europe. *Parasites & Vectors*, 7(268), 1–11. <https://doi.org/10.1186/1756-3305-7-268>
- McKinley, D. C., Miller-Rushing, A. J., Ballard, H. L., Bonney, R., Brown, H., Cook-Patton, S. C., Evans, D. M., French, R. A., Parrish, J. K., Phillips, T. B., Ryan, S. F., Shanley, L. A., Shirk, J. L., Stepenuck, K. F., Weltzin, J. F., Wiggins, A., Boyle, O. D., Briggs, R. D., Chapin, S. F., ... Soukup, M. A. (2017). Citizen science can improve conservation science, natural resource management, and environmental protection. *Biological Conservation*, 208, 15–28. <https://doi.org/10.1016/j.biocon.2016.05.015>
- Meentemeyer, R. K., Dorning, M. A., Vogler, J. B., Schmidt, D., & Garbelotto, M. (2015). Citizen science helps predict risk of emerging infectious disease. *Frontiers in Ecology and the Environment*, 13, 189–194. <https://doi.org/10.1890/140299>
- Moore, A. D., Topper, A. J., Woodward, C. W., Wood, G. E., & Long, K. L. (2019). *The mosquito census: Tracking New Zealand's mosquitoes using citizen science*. Retrieved from <https://digitalcommons.wpi.edu/iqp-all/5361>
- Muñoz, J. P., Boger, R., Dexter, S., & Low, R. (2020). Mosquitoes and public health: Improving data validation of citizen science contributions using computer vision. In N. Wickramasinghe & F. Bodendorf (Eds.), *Delivering superior health and wellness management with IoT and analytics. Healthcare delivery in the information age* (pp. 469–493). Springer Nature.
- Murindahabi, M. M., Asingizwe, D., Poortvliet, P. M., van Vliet, A. J. H., Hakizimana, E., Mutesa, L., Takken, W., & Koenraadt, C. J. M. (2018). A citizen science approach for malaria mosquito surveillance and control in Rwanda. *NJAS - Wageningen Journal of Life Sciences*, 86–87, 101–110. <https://doi.org/10.1016/j.njas.2018.07.005>
- Museum of New Zealand/Te Papa Tongarewa. (2020). *New Zealand mosquito census*. Retrieved from <https://www.tepapa.govt.nz/discover-collections/read-watch-play/science/new-zealand-mosquito-census>
- Mwangungulu, S. P., Sumaye, R. D., Limwagu, A. J., Siria, D. J., Kaindoa, E. W., & Okumu, F. O. (2016). Crowdsourcing vector surveillance: Using community knowledge and experiences to predict densities and distribution of outdoor-biting mosquitoes in rural Tanzania. *PLoS ONE*, 11(6), 1–24. <https://doi.org/10.1371/journal.pone.0156388>
- Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlenn, D., Minchin, P. R., O'Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. M., Szoecs, E., & Wagner, H. (2019). *vegan: Community ecology package*. R package version 2.5-4. Retrieved from <https://CRAN.R-project.org/package=vegan>
- Palmer, J. R. B., Oltra, A., Collantes, F., Delgado, J. A., Lucientes, J., Delacour, S., Bengoa, M., Eritja, R., & Bartumeus, F. (2017). Citizen science provides a reliable and scalable tool to track disease-carrying mosquitoes. *Nature Communication*, 8, 1–13. <https://doi.org/10.1038/s41467-017-00914-9>
- Paul, K., Quinn, M. S., Huijser, M. P., Graham, J., & Broberg, L. (2014). An evaluation of a citizen science data collection program for recording wildlife observations along a highway. *Journal of Environmental Management*, 139, 180–187. <https://doi.org/10.1016/j.jenvman.2014.02.018>
- Paupy, C., Delatte, H., Bagny, L., Corbel, V., & Fontenille, D. (2009). *Aedes albopictus*, an arbovirus vector: From the darkness to the light. *Microbes and Infection*, 11, 1177–1185. <https://doi.org/10.1016/j.micinf.2009.05.005>
- Pernat, N., Kampen, H., Jeschke, J. M., & Werner, D. (2020). Data from: Citizen science versus professional data collection: Comparison of approaches to mosquito monitoring in Germany. *ZALF Open Research Data Repository*, <https://doi.org/10.4228/ZALF.DK.151>
- Porter, W. T., Motyka, P. J., Wachara, J., Barrand, Z. A., Hmood, Z., McLaughlin, M., Pemberton, K., & Nieto, N. C. (2019). Citizen science informs human-tick exposure in the Northeastern United States. *International Journal of Health Geographics*, 18(9), 1–14. <https://doi.org/10.1186/s12942-019-0173-0>
- R Core Team. (2018). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. Retrieved from <https://www.r-project.org/>
- Roy, H. E., Rorke, S. L., Beckmann, B., Booy, O., Botham, M. S., Brown, P. M. J., Harrower, C., Noble, D., Sewell, J., & Walker, K. (2015). The contribution of volunteer recorders to our understanding of biological invasions. *Biological Journal of the Linnean Society*, 115, 678–689. <https://doi.org/10.1111/bij.12518>
- Roy-Dufresne, E., Saltre, F., Cooke, B. D., Mellin, C., Mutze, G., Cox, T., & Fordham, D. A. (2019). Modeling the distribution of a wide-ranging invasive species using the sampling efforts of expert and citizen scientists. *Ecology and Evolution*, 9, 11053–11063. <https://doi.org/10.1002/ece3.5609>
- Scholte, E. J., & Schaffner, F. (2007). Waiting for the tiger: Establishment and spread of the *Aedes albopictus* mosquito in Europe. In W. Takken & B. G. J. Knols (Eds.), *Emerging pests and vector-borne diseases in Europe* (pp. 241–260). Wageningen Academic Publishers. <https://doi.org/10.3920/978-90-8686-626-7>
- Sladonja, B., & Poljuha, B. (2018). Citizen science as a tool in biological recording – A case study of *Ailanthus altissima* (Mill.). *Swingle. Forests*, 9, 1–14. <https://doi.org/10.3390/f9010031>
- Spear, D. M., Pauly, G. B., & Kaiser, K. (2017). Citizen Science as a tool for augmenting museum collection data from urban areas. *Frontiers in Ecology and Evolution*, 5, 1–12. <https://doi.org/10.3389/fevo.2017.00086>
- Spence Beaulieu, M. R., Hopperstad, K., Dunn, R. R., & Reiskind, M. H. (2019). Simplification of vector communities during suburban succession. *PLoS ONE*, 14, 1–17. <https://doi.org/10.1371/journal.pone.0215485>
- Tarter, K. D., Levy, C. E., Yaglom, H. D., Adams, L. E., Plante, L., Casal, M. G., Gouge, D. H., Rathman, R., Stokka, D., Weiss, J., & Venkat, H. (2019). Using citizen science to enhance surveillance of *Aedes aegypti* in Arizona, 2015–2017. *Journal of the American Mosquito Control Association*, 35, 11–18. <https://doi.org/10.2987/18-6789.1>
- Tippelt, L., Walther, D., Scheuch, D. E., Schäfer, M., & Kampen, H. (2018). Further reports of *Anopheles algeriensis* Theobald, 1903 (Diptera: Culicidae) in Germany, with evidence of local mass development. *Parasitology Research*, 117, 2689–2696. <https://doi.org/10.1007/s00436-018-5938-z>
- Tyson, E., Bowser, A., Palmer, J., Kapan, D., Bartumeus, F., Martin, B., & Pauwels, E. (2018). Global mosquito alert: Building citizen science capacity for surveillance and control of disease-vector mosquitoes. Global Mosquito Alert Consortium: Report from Mosquito Task &

- Finish Group UN Sponsored Workshop, Geneva 2017. Woodrow Wilson International Center for Scholars.
- van der Velde, T., Milton, D. A., Lawson, T. J., Wilcox, C., Lansdell, M., Davis, G., Perkins, G., & Hardesty, B. D. (2017). Comparison of marine debris data collected by researchers and citizen scientists: Is citizen science data worth the effort? *Biological Conservation*, 208, 127–138. <https://doi.org/10.1016/j.biocon.2016.05.025>
- van Strien, A. J., van Swaay, C. A. M., Termaat, T., & Devictor, V. (2013). Opportunistic citizen science data of animal species produce reliable estimates of distribution trends if analysed with occupancy models. *Journal of Applied Ecology*, 50, 1450–1458. <https://doi.org/10.1111/1365-2664.12158>
- Vaux, A. G. C., & Medlock, J. M. (2015). Current status of invasive mosquito surveillance in the UK. *Parasites & Vectors*, 8(351), 1–12. <https://doi.org/10.1186/s13071-015-0936-9>
- Walther, D., & Kampen, H. (2017). The citizen science project 'Mueckenatlas' helps monitor the distribution and spread of invasive mosquito species in Germany. *Journal of Medical Entomology*, 54, 1790–1794. <https://doi.org/10.1093/jme/tjx166>
- Werner, D., Kowalczyk, S., & Kampen, H. (2020). Nine years of mosquito monitoring in Germany, 2011–2019, with an updated inventory of German culicid species. *Parasitology Research*, 119(9), 2765–2774. <https://doi.org/10.1007/s00436-020-06775-4>
- Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. Springer Verlag. <https://doi.org/10.1007/978-0-387-98141-3>
- Zielke, D. E., Ibanez-Justicia, A., Kalan, K., Merdic, E., Kampen, H., & Werner, D. (2015). Recently discovered *Aedes japonicus japonicus* (Diptera: Culicidae) populations in the Netherlands and northern Germany resulted from a new introduction event and from a split from an existing population. *Parasites & Vectors*, 8(40), 1–19. <https://doi.org/10.1186/s13071-015-0648-1>

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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