The citizen science project ‘Mückenatlas’: contributions of opportunistic data collection to mosquito research in Germany

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DECLARATION

The scientific work presented in this thesis was conducted from January 2019 to August 2021 at the Leibniz Centre for Agricultural Landscape Research (ZALF) in Müncheberg, in collaboration with the Institute of Biology, Freie Universität Berlin (FU) and the Friedrich-Loeffler-Institut (FLI) in Greifswald – Insel Riems, Germany. The work was supervised by Dr. Doreen Werner, head of the (Semi)aquatic Biodiversity group at ZALF, and Prof. Dr. Jonathan M. Jeschke, head of the Ecological Novelty group at FU.

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This dissertation is dedicated to my husband Tim. Thank you for believing in me and always supporting me.

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II SUMMARY

Since the first coining of the term in the mid-1990s, citizen science – the involvement of the public in scientific research – has become an emerging field, both as a research approach and as a discipline (the *science of citizen science*) by itself. Publications on the topic have increased in number nearly exponentially over the last 15 years, and the discourse about definition, applicability and transformative power involving experts from social and natural sciences to politics is in full swing. In the meantime, practical citizen science has conquered the world, especially to monitor biodiversity, with hundreds of projects popping up on nearly every continent, benefitting from and building on the already existing fundament of naturalists and science-loving people.

Amidst this movement, the 'Mückenatlas' (German for 'mosquito atlas') was launched in 2012, shortly before citizen science gained momentum in Germany. The goal of the 'Mückenatlas' is to support mapping the occurrence and distribution of native and introduced mosquito species. Therefore, people collect and submit physical mosquito samples to the responsible research institutions. In return, participants receive an individual answer with information about the biology of the captured species and, if desired, a personal marker on the collectors' map on the 'Mückenatlas' website. In my thesis, I evaluated the project from three perspectives, based on current controversies in citizen science: as a monitoring method (Chapter 2), as a data source (Chapters 3 and 4), and as a public outreach activity (Chapter 5). The general aim of the dissertation was to assess the contributions of the opportunistic data collection of the 'Mückenatlas' project to mosquito research in Germany.

In Chapter 2, the 'Mückenatlas' performance was evaluated relative to a conventional monitoring approach. In this part, the opportunistic 'Mückenatlas' data (*passive monitoring*) and the systematic trapping by scientists (*active monitoring*) were compared with respect to their habitat coverage, reported species richness, species discovery time, and the capability to detect invasive mosquito species. The results show that *active monitoring* allows for a better coverage of land use types and species richness, whereas the *passive monitoring* approach focuses on urban areas and can very well detect invasive species. The findings suggest that the inclusion of citizen science in formal mosquito monitoring programmes can compensate for shortcomings of exclusively professional monitoring methods.

Chapters 3 and 4 focus on the opportunistic data collection of the 'Mückenatlas' and its applicability in research. In Chapter 3, anthropogenic and environmental factors were identified as drivers of the spatio-temporal variation in the numbers of submissions. However, these factors influence the behaviour of the participants at the same time, which demonstrated the complexity in explaining biases. Nevertheless, with appropriate methods to account for such biases, opportunistic data collection contributes to knowledge gain. Chapter 4 is an analysis of nearly 17,000 mosquito indoor samples submitted by participants. To assess the explanatory power of the data, I compared the indoor mosquito communities of different levels of urbanisation. The results highlight that opportunistic data cannot only confirm what is known about urban mosquito ecology, but also provide new insights into indoor mosquito biodiversity. Moreover, the study indicated that citizen science leads to alternative ways of knowledge production.

Chapter 5 demonstrates the influence of the media in triggering participation by citizen scientists. There is a positive temporal and spatial correlation of numbers of media reports and numbers of submissions. The findings also suggest that the contextualisation and style of the titles and texts of media reports, as well as an already increased media and public attention towards mosquito topics, increase the responsiveness of participants and thus the numbers of submissions.

The results of the studies indicate that the opportunistic data collection of the 'Mückenatlas' can make crucial contributions to mosquito research, especially to gaining knowledge about species occurrence due to the sheer number of samples submitted. The critical review of the results enabled me to suggest when and how to include citizens in formal mosquito monitoring programmes, which biases and patterns to consider in the data analysis, and how communication strategies might affect participation and shape the data. Placed in a broader context, the results of the dissertation imply that the 'Mückenatlas' approach can also be adopted for monitoring other taxa to enlarge biodiversity data collections. Especially in underrepresented regions of biodiversity research or in fields related to public health, mass participation of citizens could fill data gaps or even collect information for the first time.

Even a project that focuses mainly on collecting data, such as the 'Mückenatlas', breaks new ground in knowledge production and leads to new research questions. In this way, citizen science – as a research approach and discipline – confirms the potential to democratise science and could contribute to reducing the distance between science and society.

Keywords: Biodiversity, Citizen Science, Invasion Biology, Mosquito Monitoring, Mosquito-borne Diseases, Public Engagement

II ZUSAMMENFASSUNG

Seit der Prägung des Begriffs *Citizen Science* (übersetzt: Bürgerwissenschaften) Mitte der 1990er Jahre, hat sich die Wissenschaft in Zusammenarbeit mit Bürgerinnen und Bürgern als Forschungsansatz an sich, aber auch als eigenständige Disziplin (*science of citizen science*), stark entwickelt. Veröffentlichungen zum Thema nahmen in den letzten 15 Jahren fast exponentiell zu und der Diskurs zwischen Experten aus Wissenschaft, Politik und Gesellschaft über Definitionen, Anwendbarkeit und transformative Kraft ist in vollem Gange. Währenddessen hat die praktische Anwendung von *Citizen Science* bereits globale Maßstäbe erreicht: Hunderte von Projekten auf nahezu allen Kontinenten, insbesondere zur Aufnahme der biologischen Vielfalt, profitieren von der bereits vorhandenen Gemeinschaft von Naturforschern und wissenschaftsbegeisterten Menschen.

Inmitten dieser weltweiten Bewegung und kurz bevor *Citizen Science* auch in Deutschland zunehmend an Dynamik gewann, startete im Jahr 2012 der Mückenatlas. Ziel des Mückenatlas ist es, Vorkommen und Verbreitung einheimischer und eingeführter Stechmückenarten zu kartieren. Dafür fangen Bürgerinnen und Bürger Stechmücken und schicken sie per Post an die zuständigen Forschungseinrichtungen. Im Gegenzug erhalten sie eine individuelle Antwort mit Informationen zur gefangenen Art und, falls gewünscht, einen personalisierten Marker auf der Karte der Sammler der Projekt-Website.

In der vorliegenden Dissertation habe ich den Mückenatlas aus drei, auf aktuellen Kontroversen basierenden Blickwinkeln betrachtet: als Monitoringmethode (Kapitel 2), als Datenquelle (Kapitel 3 und 4) und als Instrument der Öffentlichkeitsarbeit (Kapitel 5). Das übergeordnete Ziel der Dissertation war es, die Beiträge der opportunistischen Datensammlung des Projekts zur Stechmückenforschung in Deutschland zu bewerten.

In Kapitel 2 wurde die Leistung des Mückenatlas als Monitoring-Methode gegenüber eines konventionellen Ansatzes beurteilt. Die opportunistischen Mückenatlas-Daten *(passives Monitoring)* und die systematischen Fallenfänge durch Wissenschaftler (*aktives Monitoring*) wurden jeweils im Hinblick auf die Abdeckung verschiedener Habitate, den nachgewiesenen Artenreichtum, den Zeitaufwand für die Entdeckung des Artenreichtums und die Detektion invasiver Mückenarten verglichen. Die Ergebnisse zeigen, dass *aktives Monitoring* eine bessere Abdeckung von Habitaten ermöglicht und mehr Arten erfasst, wohingegen das *passive Monitoring* mehr Daten aus städtischen Gebieten liefert und sehr gut zum Nachweis invasiver Arten geeignet ist. Die Ergebnisse deuten darauf hin, dass die Integration von *Citizen Science*-Komponenten in offizielle Stechmücken-Überwachungsprogramme die Schwächen professioneller Monitoringmethoden ausgleichen kann.

In Kapitel 3 und 4 ist die opportunistische Datensammlung des Mückenatlas alleiniger Forschungsgegenstand. Als Verursacher von räumlich-zeitlichen Variationen in den Einsendungen wurden dazu in Kapitel 3 anthropogene und Umweltvariablen identifiziert, die nicht nur direkt wirken, sondern auch gleichzeitig das Verhalten der Teilnehmenden beeinflussen. Die Interpretation der Ursache von Verzerrungen ist dementsprechend komplex. Wenn solche Verzerrungen aber mit geeigneten Methoden berücksichtigt werden, kann die opportunistische Datenerhebung zum Erkenntnisgewinn beitragen.

Um die Aussagekraft der Daten zu bewerten, wurden in Kapitel 4 fast 17.000 Stechmückenproben aus den Innenräumen der Teilnehmenden ausgewählt. Mit diesem Teildatensatz wurden Stechmückengemeinschaften verschiedener Urbanisierungsgrade verglichen. Die Ergebnisse zeigen, dass die Mückenatlas-Daten bestätigen, was bereits über die Ökologie von Stechmücken bekannt ist und zudem ganz neue Erkenntnisse über die Biodiversität von Stechmücken in Innenräumen liefern. Darüber hinaus belegt die Studie, dass *Citizen Science* alternative Wege bietet, Wissen zu generieren.

Kapitel 5 demonstriert den Einfluss der Medien bei der Gewinnung von Teilnehmenden für *Citizen Science*-Projekte. Die Zahl der Medienberichte über und Einsendungen an den Mückenatlas sind zeitlich und räumlich positiv korreliert. Die Ergebnisse deuten außerdem darauf hin, dass die Kontextualisierung und der Stil der Titel und Fließtexte von Medienberichten sowie eine bereits erhöhte Aufmerksamkeit der Medien und der Öffentlichkeit gegenüber Stechmücken die Teilnahmebereitschaft und damit die Zahl der Einsendungen erhöhen.

Insgesamt zeigen die Studienergebnisse, dass die opportunistische Datensammlung des Mückenatlas einen entscheidenden Beitrag zur Mückenforschung leistet, insbesondere bei den Nachweisen von Artvorkommen durch die schiere Anzahl der eingereichten Proben. Aus einer kritischen Diskussion der Ergebnisse werden Vorschläge abgeleitet, wann und wie

Bürger in offizielle Mückenüberwachungsprogramme einbezogen werden sollten, welche Verzerrungen und Muster bei der Datenanalyse zu berücksichtigen sind und wie Kommunikationsstrategien die Teilnahme und die Daten beeinflussen können. In einem übergeordneten Kontext betrachtet, deuten die Ergebnisse der Dissertation darauf hin, dass der Mückenatlas-Ansatz auch für das Monitoring anderer Arten funktionieren kann, um die Datengrundlage zur biologischen Vielfalt zu erweitern. Insbesondere in global unterrepräsentierten Regionen der Biodiversitätsforschung oder in Bereichen der öffentlichen Gesundheit könnte die massenhafte Beteiligung von Bürgerinnen und Bürgern Datenlücken schließen oder sogar zum ersten Mal überhaupt Informationen liefern.

Selbst ein auf das Sammeln von Daten fokussiertes Projekt wie der Mückenatlas beschreitet andere Wege in der Wissensproduktion und führt zu neuen Forschungsfragen. Damit bestätigt *Citizen Science* – als Forschungsansatz und -disziplin – das Potenzial zur Demokratisierung der Wissenschaft und könnte dazu beitragen, die Kluft zwischen Wissenschaft und Gesellschaft zu verringern.

Stichworte: Biodiversität, Bürgerwissenschaften, Invasionsbiologie, Stechmücken-Monitoring, Stechmücken-assoziierte Krankheitserreger, Partizipation

III THESIS OUTLINE

The dissertation is subdivided into a **General introduction**, four research **Chapters,** and a **General discussion**. The General introduction starts with the background of citizen science followed by sections on its application in biodiversity research and data issues before giving context to the research on citizen scientists. Subsequently, the motivation, objectives, and work plan of the dissertation are described. The following individual chapters each represent a manuscript already published, or, in case of Chapter 5, submitted and under revision. In the General discussion, the results of the research chapters are synthesised, evaluated, and discussed before concluding remarks and an outlook to possible future research are given.

IV LIST OF PUBLICATIONS WITH AUTHOR CONTRIBUTIONS

AUTHORS

Author of this cumulative thesis: Nadja Pernat (NP)

CO-AUTHORS

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Jonathan M. Jeschke (JMJ)

Helge Kampen (HK)

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The following publications derived from this thesis:

Pernat N, Kampen H, Jeschke JM, Werner D (2021) Citizen science versus professional data collection: Comparison of approaches to mosquito monitoring in Germany. *Journal of Applied Ecology* 58: 214-223. https://doi.org/10.1111/1365-2664.13767.

NP, HK and DW devised the main conceptual idea. NP planned and performed the data analysis. HK and DW provided the mosquito data and supervised the project. NP led the writing of the manuscript with much input from HK, JMJ and DW. All authors contributed critically to the manuscript drafts.

Pernat N, Kampen H, Ruland F, Jeschke JM, Werner D (2021) Drivers of spatio-temporal variation in mosquito submissions to the citizen science project 'Mückenatlas'. *Scientific Reports* 11: 1356. https://doi.org/10.1038/s41598-020-80365-3.

NP conceptualised the work, analysed and interpreted the data and led the writing. FR contributed to data analysis, interpreted the data and revised the manuscript. JMJ provided advice, interpreted the data and revised the manuscript. HK and DW designed the study, raised funds, provided the data, interpreted the data and revised the manuscript. All authors contributed critically to the manuscript drafts.

Pernat N, Kampen H, Jeschke JM, Werner D (2021) Buzzing homes: Using citizen science data to explore effects of urbanization on indoor mosquito communities. *Insects* 12: 374. https://doi.org/10.3390/insects12050374.

NP conceptualised the work, developed the methodology with support from JMJ, analysed and interpreted the data, created the visualisations and wrote the original manuscript draft. DW, HK and JMJ supervised the study. DW and HK administrated the project and acquired the funding. All authors contributed critically to the manuscript drafts.

Pernat N, Kampen H, Zscheischler J, Ostermann-Miyashita EF, Jeschke JM, Werner D: How media presence triggers participation in citizen science – the case of the mosquito monitoring project 'Mückenatlas'. Under revision at: *PLOS ONE*.

NP conceptualised the work and conducted the formal analysis together with EFOM. NP, JZ and JMJ developed the methodology. NP created the visualisations and wrote the original manuscript draft. DW, HK and JMJ supervised the study. DW and HK administrated the project and acquired the funding. All authors contributed critically to the manuscript drafts.

V. TABLE OF CONTENTS

Chapter 1 | General introduction

1.1 Citizen science – from niche to mainstream?

Citizen science is a working format to involve people outside of institutional science in the research process to create knowledge together. The term *citizen science* goes back to the 1990s and was simultaneously coined by two persons, Alan Irwin and Rick Bonney (Irwin, 1995; Bonney, 1996). But – according to Strasser et al. (2018) – the research method itself originated from two historical developments. First, while methods and devices in science evolved over time and the possibility for individualists and naturalists to conduct science without costly and sophisticated instruments diminished, research institutes emerged and with it the profession of scientists. Subsequently, amateur scientists pursued their passion for research outside of institutions, but often in collaboration with them, e.g. as volunteers. Second, antiwar and equality movements (e.g. on gender and race) in the 1960s and 1970s in the United States led to demands to align scientific research with the interests of citizens and to bottom-up actions by communities that felt neglected by the government's scientific agendas.

Both historical developments can still be recognised today, for example in approaches to develop a typology of citizen science programmes. Bonney et al. (2009) grouped projects according to their centre of lead, such as *contributory projects*, when led by a scientific institution, or as *co-created projects*, when non-scientists are at least partly the initiators. Other typologies focus on the projects' objectives and characters (Wiggins and Crowston, 2011) or the participants' activities (Strasser et al., 2018). In addition, attempts have been made to define citizen science and related terms, which have provoked ambivalent reactions in the scientific community (Eitzel et al., 2017; Auerbach et al., 2019; Heigl et al. 2019) and continue to be debated (Haklay et al., 2021).

The objectives of citizen science are twofold. On the part of science, expected benefits include increasing the spatio-temporal coverage of data collections, accessing untapped knowledge and places (wisdom of crowds), addressing research questions that would otherwise be unfeasible due to the existing personnel and financial constraints of institutional science, and identifying research questions that are relevant from a societal perspective

(Devictor, Whittaker and Beltrame, 2010; Cleary et al., 2016; Steinke, van Etten and Zelan, 2017; Pocock et al., 2018b; Butkevičienė et al., 2021; Putman et al., 2021). On the policy and societal side, the objectives are geared towards *democratising science* by using citizen science as a participatory format to raise understanding of and interest in science, increase social capital, draw attention to societal or environmental problems, and empower individuals or communities (Bonney et al., 2014, 2016; Forrester et al., 2017; Ballard et al., 2018; Butkevičienė et al., 2021).

From 2012 onwards, the term citizen science became globally accepted due to an increase in publications, funding, and projects (Vohland et al., 2021a). In Germany, the first funding scheme was initiated by the Federal Ministry of Education and Research in 2014 that supported single projects as well as a national consortium to develop a citizen science strategy and infrastructure for the advancement of the field (Pettibone et al., 2016). In 2018, the resulting web platform www.buergerschaffenwissen.de already contained 96 projects (Ostermann-Miyashita et al., 2019). Simultaneously to the advent of citizen science in Germany, funding programmes and platforms were launched in many European countries. Finally, activities culminated in a continent-wide citizen science organisation, the European Citizen Science Association (ECSA) (Vohland et al., 2021a). Similar organisations have formed for example in Asia, Australia, and North America, and a topic-specific journal, *Citizen Science in Theory and Practice*, was launched in 2016 (Bonney, Cooper and Ballard, 2016). In this process, the *science of citizen science* was born, and research is now not only conducted with but also about citizen science (Vohland et al., 2021b). Citizen science is also believed to have the potential to contribute to the achievement of the UN Sustainable Development Goals (Fritz et al., 2019).

On the flipside, citizen science faces some issues in achieving the ideal envisioned by its proponents. From a research perspective, concerns focus mainly on the quality of data collections or analysis (Kosmala et al., 2016), but also on the whole data life cycle and management (Bowser et al., 2020). Starting from data protection, data privacy, and intellectual property further ethical questions arise, such as the instrumentalisation and exploitation of citizens through science, unbalanced power relationships between volunteers and researchers as well as an adequate acknowledgement of the citizens' contribution (Tauginienė et al., 2021). Furthermore, the demographics of citizen scientists reflect the overrepresentation of high-income and educated white populations in academic research which questions the premise that citizen science is accessible to all (Cooper et al., 2021).

The rise of citizen science has coincided with the transformative power of the internet, which provides the digital tools to advance participatory processes. In science, the accelerated technological progress allows scientists to facilitate the public's involvement in projects across a range of scientific disciplines through websites or applications on smart phones. E-mail and social media enable easier communication with the public (Newman et al., 2012). Among the first online projects were *FoldIt* (protein folding exercises), *Galaxy Zoo* (galaxy classification from images), and *eBird* (interactive database for bird observations), proving the feasibility and success of citizen science by reaching large numbers of participants and producing renowned scientific output (Cooper et al., 2010; Fortson et al., 2012; Wood et al., 2012). Today, citizen science is mainstream (Callaghan et al., 2019): according to a scientometric study from Pelacho et al. (2020), the annual growth rate of citizen science publications over the last decade has been consistently around 40 percent. By 2019, the world's biggest platform for citizen science projects *Scistarter* listed over 4,400 projects worldwide from around 25 science disciplines (European Commissions, 2021).

1.2 Citizen science in biodiversity research

Monitoring biodiversity

Just as long as amateur science goes back in history, so does the involvement of volunteers in biodiversity research. For example, records of the timing of the cherry blossom reach back 1,200 years in Japan (Kobori et al., 2015). The *North American Bird Phenology Program* contains data on bird migrations from 1890 onwards, and the hand-written records are – again within a citizen science context – in the process of being digitised (Mayer, 2010). Today, projects range from continuous monitoring of the global occurrence of all taxa (e.g. *iNaturalist*) to monitoring a single, rare species (Havens et al., 2012); from identifying animals from pictures taken by camera traps on the other side of the world (Swanson et al., 2016) to documenting how many prey the pet cat has brought home (Kays et al., 2020); from local individuals managing transects several times a year and over many years (Richter et al., 2018) to one-day *Bioblitzes* engaging masses of people (Lundmark, 2003).

Accordingly, the programmes vary so much in their objectives, degree of structuring, complexities of tasks, and duration of participation that the diversity of projects can hardly be classified (Pocock et al., 2017). Kullenberg and Kasperowski (2016) found publications on citizen science mainly being connected to voluntary monitoring for ecological, environmental, geographical, and biodiversity conservation studies. Yet, Hecker, Garbe and Bonn (2018) reported that most biodiversity-related citizen science projects mainly involve citizens by recording observations and collecting data, less in other parts of the scientific process, such as study design or data analysis.

Digitalisation has also initiated a strong increase in biodiversity-related citizen science projects through the usage of smartphone apps (e.g. Sladonja and Poljuha, 2017), web-platforms (e.g. van der Wal et al., 2016), affordable camera or sensor devices (e.g. Zarybnicka, Sklenicka and Tryjanowski, 2017; Locke et al., 2019), or social media (Bíl et al., 2020). Moreover, the continuous progress in artificial intelligence keeps facilitating the participation in internet-based citizen science projects, e.g. through image-based species identification (Wäldchen, Mäder and Cooper, 2018). This results in a massive increase of citizen science data: Roy et al. (2012) reported an estimated 85 percent of the biodiversity data on species level used by the United Kingdom government is volunteer-based, and the share of citizen science information in GBIF (Global Biodiversity Information Facility) data has increased to over 50 percent in 2019 (Figure 1).

In the context of unprecedented global biodiversity loss, this monitoring data is urgently needed to assess the impacts of anthropogenic activities on biodiversity and ecosystem services. Due to the insufficient global biodiversity data, environmental changes cannot be estimated as quickly as they happen (Pocock et al., 2018a). Citizen science approaches in biodiversity monitoring could be one solution to scale up spatio-temporal coverage and the amount of data in a cost-efficient way. In addition to the added value for research, including citizens in biodiversity monitoring can foster partnership between stakeholders in the project and lead to behavioural change of how people interact with their environment (Oberhauser and Prysby, 2008; McKinley et al., 2017).

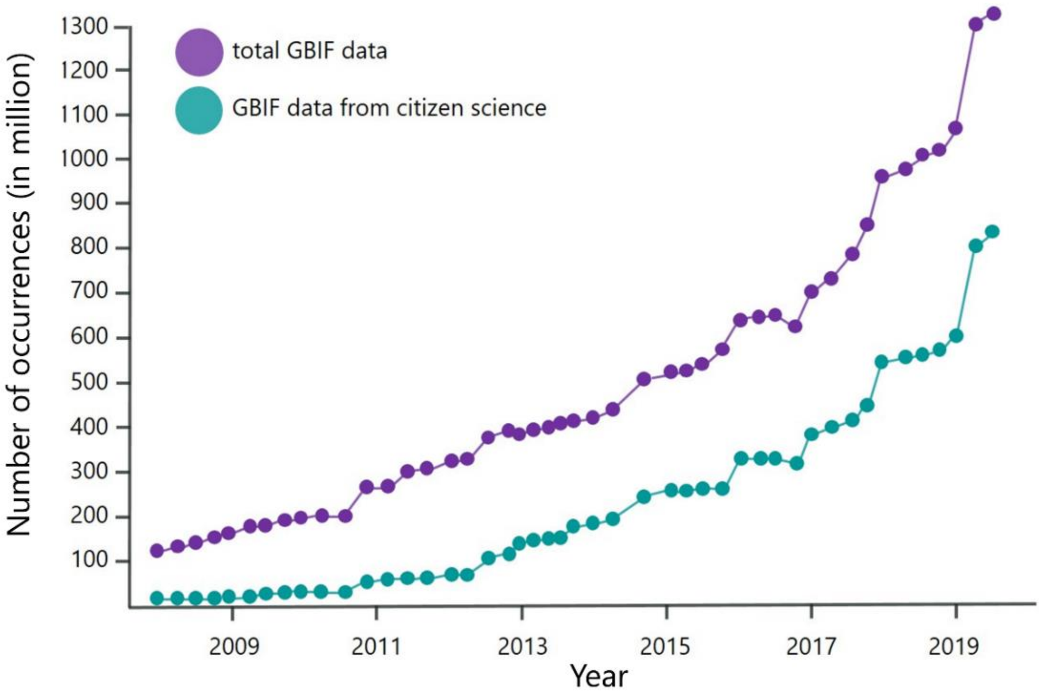

Figure 1: Number of species occurrences in total GBIF data and from citizen science sources separately. Figure adapted from: John Waller, Citizen Science on GBIF (2019). Available at: https://data-blog.gbif.org/post/citizen-science-on-gbif-2019/ (accessed on 15 March 2021).

Involvement of the public has already proven to be particularly useful in two areas of biodiversity monitoring in which ecologists struggle with the lack of real-time data: urban ecology and invasion biology. By providing data from private homes and gardens in urban areas, to which scientists have no access, citizens can speed up the research on how species communities respond to fast-paced urbanisation (Spear, Pauly and Kaiser, 2017; Putman et al., 2021). The public has also contributed significantly to research on invasive alien species (Encarnação et al., 2021), both through first detections and by helping to track the frontline of a spreading invader (Goldstein et al., 2014; Malek et al., 2018).

In North America and Europe, volunteering in biodiversity research is relatively well established (Frigerio et al., 2021) and already contributed to prominent findings. For example, first evidence for biomass loss of insects that resulted in a global awakening was provided by an amateur scientist collective in Germany (Hallmann et al., 2017; Vogel, 2017). By contrast, although countries in Africa and Asia are strongly affected by biodiversity loss due to climate change and uncontrolled urbanisation, these continents are underrepresented in data, because ecology research is biased towards temperate woodlands, natural reserves, and prosperous nations (Martin, Blossey and Ellis, 2012). Therefore, proposals for a globally balanced biodiversity monitoring with the help of a worldwide community of citizen scientists are increaseingly being put forward for discussion (e.g. Chandler et al., 2012; Dunn and Beasley, 2016; Pocock et al., 2018a, 2018b).

Applicability of citizen science data

Although several studies demonstrated complementary or similar performance of citizen science to professionally, systematically collected data (e.g. Meentemeyer et al., 2015; Mair et al., 2017; Horns, Adler and Şekercioğlu, 2018; Henckel et al., 2020; Krabbenhoft and Kashian, 2020), doubts about data quality are one of the main reasons why parts of the scientific community are sceptical about citizen science (Kosmala et al., 2016; Bowser et al., 2020). Large-scale biodiversity monitoring projects often suffer from data biases due to the recording behaviour of the citizen scientists, which is in turn related to the respective survey design of the different projects. Kelling et al. (2019) provide a survey design classification of citizen science programmes as unstructured, semi-structured, and structured with respect to objectives, flexibility and data standards.

Structured programmes are characterised by a strict sampling protocol and survey design. In projects organised by the non-governmental organisation Earthwatch Institute, for example, citizens conduct systematic field studies together with scientists (Chandler et al., 2017). Semi-structured citizen science often includes species atlases, such as the German butterfly monitoring scheme or *eBird* (Sullivan et al., 2014; Richter et al., 2018), and gather some observation information during the data collection process. This happens along a continuous gradient of observation flexibility, such as taxonomic checklists, predefined locations, or selected time intervals. Unstructured programmes, in contrast, are characterised by minimal sampling protocols that usually require no training, are mostly internet-based, and often achieve mass participation (e.g. *iNaturalist*). The data resulting from a collection process with little or no sampling design are called *opportunistic*, thereby referring to the unforeseen behaviour of the citizen scientists when and where to participate. In general, data bias increases with protocol flexibility, resulting in a trade-off between the time and effort required to vet the data and the personal freedom of participants – the latter demonstrably contributing to the success and massive data collections of unstructured projects (Geldmann et al., 2016; Pocock et al., 2017).

While bias is reduced by design in structured programmes, observation processes of broad-scale unstructured and semi-structured projects generate variation in space and time. Spatial bias, the uneven sampling over space, mostly arises by the participants' site-selection behaviour. They may choose sites where they know or suspect that there are (abundant) specimens of the focal or of particular interesting species (Boakes et al., 2010; Booth et al., 2011; Tulloch and Szabo, 2012; Tulloch et al., 2013), such as nature preserves with high biodiversity (Dennis and Thomas, 2000; Botts et al., 2011; Tulloch et al., 2013; Boakes et al., 2016), locations that are close to or directly at home (Botts et al., 2011; Fletcher et al., 2019), which are easily accessible by roads or paths as well as through public transport (Tulloch and Szabo, 2012; Sequeira et al., 2014; Mair and Ruete, 2016; Tiago et al., 2017), or that are simply scenic (Romo, García-Barros and Lobo, 2006; Millar, Hazell and Melles, 2019). Temporal bias, the irregular recording effort over time, might result from weather variability or time of season that determine the activity of participants. Other factors reported are the availability of the citizen scientists, e.g. increased engagement at weekends (Courter et al., 2013) or light conditions during daytime (Paul et al., 2014).

Decisions of when and where to participate also feed into observation or detection biases caused by irregular sampling effort and intensity. These include variation in detectability – the probability to detect and identify a species that is present – and taxonomic bias. For instance, participants may visit sites only at times, when a species is definitely at the location (e.g. breeding sites) or only look for or report rare species (Booth et al., 2011; Paul et al. 2014; Ward, 2014; Robinson et al., 2018; Johansson et al., 2020). Lastly, interobserver skills lead to bias in the data, e.g. by participants' differences in the level of expertise or the effort they put into the task (Kelling et al., 2015b; Johnston et al., 2017).

To achieve one of the main objectives of unstructured biodiversity citizen science programmes, i.e. mapping species distribution, dealing with variation and bias is required to produce reliable and interpretable results. Instruments to check for biases during data processing (e.g. upload to a database) are automated filters (Sullivan et al., 2014), expert validation (correctly recorded) and verification (correctly determined) (Palmer et al., 2017; Soroye, Ahmed and Kerr, 2019), and artificial intelligence such as probability testing or automated, image-based species identification (Kelling et al., 2015a; Wäldchen, Mäder and Cooper, 2018; Muñoz et al., 2020), or a combination thereof. At the data analysis stage, biases can be detected and compensated for through statistical methods, which, in principle, are the simpler the more structured the data is collected and vice versa (Callaghan et al., 2019; Kelling et al., 2019). The development of methods to draw reliable ecological conclusions from citizen science data has significantly contributed to the increased scientific output in the citizen science discipline. Milestone studies, such as how to generally deal with *noisy* citizen science data (Isaac et al., 2014), the comparison of a multitude of modelling approaches (Bird et al., 2014), or the demonstration of an integrated validation process to ensure data quality (Kelling et al., 2015a) laid the foundation for rapid methodological progress.

1.3 The citizen scientists in biodiversity research

Participant engagement affects the research process

As variable as the topics, scope, level of involvement, and duration of citizen science projects are, so are the people who take part. Common research questions of studies on citizen scientists deal with what motivates people to initially participate or sustain in citizen science programmes, achievement of educational goals, such as knowledge gain, behavioural changes, and shifts in attitudes towards science, or patterns of their behaviour, often in association with participant demographics.

Biodiversity project participants are rather middle-aged with higher levels of education and income (Crall et al., 2013; Land-Zandstra et al., 2016; Mac Domhnaill, Lyons and Nolan, 2020), and gender ratios differ by project (Booth et al. 2011; Crall et al., 2013; West and Pateman, 2016; Domroese et al., 2017). Ethnical groups other than *white* are strongly underrepresented (Geoghegan et al., 2016; Merenlender et al., 2016; Pateman, Dyke and West, 2021). Promoting diversity and inclusiveness is increasingly discussed (e.g. Sorensen et al., 2019; Paleco et al., 2021) in the course of which the prestigious National Audubon Society has already renamed citizen science as *community science* (National Audubon Society, 2018).

Top motivations to participate in biodiversity-related projects are learning new skills, supporting the environment, interest in science and nature, and contributing to science (Geoghegan et al., 2016; Land-Zandstra et al., 2016; West and Pateman, 2016; Domroese et al., 2017; Schuttler et al., 2018). Maund et al. (2020) showed that these intrinsic motivations remain the same, even if the level of involvement of the participants differs strongly. Motivations are also associated with demographics: overrepresented demographic groups of citizen scientists are motivated by their values, such as helping research or the environment, whereas underrepresented groups indicate rather egoistic or extrinsic drivers, e.g. career development (West, Dyke and Pateman, 2021).

Biodiversity citizen science not only supports research, but also aims to increase scientific literacy and brings about behavioural and attitude changes towards science and the environment (McKinley et al., 2017). Peter, Diekötter and Kremer (2019) reviewed 14 matching articles on biodiversity citizen science projects for individual participant outcomes and reported 50 percent of them providing evidence for knowledge gain and changes in behaviour or attitudes, respectively. A similar study carried out by Schuttler et al. (2017) analysed 22 applicable publications and found in less than 36 percent of them significant positive changes in knowledge gain and behaviour. These two studies highlight the very small proportion of citizen science projects that investigate the learning outcomes of their participants, indicating that these types of investigations are only just emerging.

Studies on participant behaviour in environmental citizen science investigate patterns of participation to inform scientists about when, where, how, and what citizens observe and which factors influence these patterns. For example, the application of behaviour metrics found clusters among participants following the Pareto principle, i.e. a few participants contribute the majority of data, whereas the majority of people only join the programmes for a few days (Ponciano and Brasilieiro, 2014; Boakes et al. 2016; Seymour and Haklay, 2017). However, when removing the *dabblers* (according to Eveleigh et al. (2014) colloquial for people who contribute only a few times) from an opportunistic dataset, the clusters dissolve and the variation in recording behaviour becomes as continuous as one would expect from the distribution of the diverse characteristics in individual engagement (August et al., 2020).

The who, why, and how of participation is not only interesting from a social science perspective. It is presented here because of the strong intertwining of the citizen scientists' participation patterns with the scientific process and the data structure. For instance, participant behaviour induces biases, and in many cases variables such as recorder effort or expertise are used as covariates to account for these biases when applying citizen science data in species distribution research (Johnston et al., 2017). Probability and frequency of participation can be projected by modelling with variables, such as participant training or motivation (Tulloch et al., 2013; August et al., 2019). As a last example, demographics of citizen scientists and project design can be mutually dependent (Burgess et al., 2015; Maund et al. 2020) and even be used as predictors of each other (Parrish et al., 2019).

Strategies for participant recruitment: if you build it, will they come?

Findings about the citizen scientists' demographic background, motivations, and behaviour are directly incorporated into studies aiming at recommendations for designing citizen science projects (Dickinson et al., 2012). If both sides – citizens and scientists – support the activity of the other, everyone benefits, and general statements can be made about some of the prerequisites for such mutually beneficial projects (Golumbic, Baram-Tsabari and Koichu, 2019). Important factors to initiate and sustain participation are a clear project organisation, ongoing feedback and easy communication with participants on equal terms, functioning technology with a good user experience, and an appreciative presentation of the contributions of the citizens (Rotman et al., 2014; Sullivan et al., 2014; Locke et al., 2019; Lowry et al., 2019). However, in addition to meeting the expectations shaped by the values and social backgrounds of potential citizen scientists, it is paramount that the project is known at all (Hobbs and White, 2012). The media can be a suitable means of drawing attention to the project and trigger participation (Chu, Leonard and Stevenson, 2012; Dickinson et al., 2012; van Vliet, Bron and Mulder, 2014).

The choice of media channels and the communication strategy depends on the respective project goals and topics, as well as on the targeted groups of participants. Project leaders will face a trade-off in the ratio of participants that sign up and those that are really engaged and continuously work on the tasks, depending on the communication strategy they chose. For example, by applying broad-scale campaigns through mass and social media, many participants may register, but a majority will not become active or will drop out soon (Crall et al., 2017). By contrast, when specifically targeting communities through (local) outreach activities (e.g. by community services), fewer citizen scientists may be recruited over space and time, but they then may actually participate more intensely and, for instance, provide a lot of data (Robson et al., 2013; Davis, 2018). The choice of media might also influence the socio-economic groups that are reached. For example, by reviewing the diverse citizen science activities of the Open Air Laboratories (OPAL), Davies et al. (2016) found that deprived communities could hardly be recruited through traditional media, but were better persuaded to get involved by face-to-face communication through local non-profit or governmental organisations as intermediaries.

The literature on media strategies for recruiting citizen scientists is still sparse (exceptional studies are cited above). Insights and best-practices from science communication, for example on how to comprehensibly communicate research results or motivate people to join a science event, can give guidance. For biodiversity-related citizen science, however, the strategies must be adapted considering that the potential participants are expected to do much more than just be present or join the dialogue in the short term.

1.4 Citizen science and mosquito research at the interface of biodiversity and public health

Mosquito-related citizen science

There are around 3,500 mosquito species worldwide, some of which can transmit pathogens that affect around 100 million people every year (World Health Organization, 2020). Several driving factors connected to human activities aggravate the situation and promote these mosquito species, which prefer humans as hosts and therefore cause most cases of human infections (Takken and Verhulst, 2013; Rose et al., 2020). The change from natural to urbanised habitats, climate warming, globalisation, and travel result in the expansion of mosquitoes and increase the risk of pathogen transmission to humans (Jácome et al., 2019).

These anthropogenic impacts do not only affect less developed countries in subtropical and tropical regions that have been fighting diseases such as malaria, yellow fever, or dengue for decades. Even in more temperate zones, some of these mosquito-borne diseases have (re)emerged in recent years, despite the control of mosquito populations with DDT in the mid-20th century and the loss of suitable habitats due to the long history of wetland drainage (Medlock and Vaux, 2015; Rochlin et al., 2016). In Europe, for example, autochthonous cases of chikungunya were reported from Italy (2007, 2017) and France (2010, 2014, 2017), and of dengue from Croatia (2010), France (2010, 2013-2015 and 2018), Portugal (Madeira, 2012-2013), and Spain (2018) (Papa, 2019). All disease cases were associated with established vector populations of invasive *Aedes* species, such as the Asian tiger mosquito (*Aedes albopictus*) or the yellow fever mosquito (*Aedes aegypti*), that ingested the respective pathogen from infected travellers.

West Nile virus is one of the most frequently transmitted arboviruses and the cause of most human cases of mosquito-borne disease in Europe. Several outbreaks have been reported since the 1990s with the most recent peak of over 2,000 human infections in 2018 (EU/ EAA and neighbouring countries), mainly in Italy, Serbia, and Greece (European Centre for Disease Prevention and Control (ECDC), 2018). Presumably, optimal conditions were given for mosquito larval development by particularly high precipitation and for virus extrinsic incubation by particularly high temperatures (Papa, 2019). In North America, West Nile virus expanded rapidly throughout the United States after its introduction into New York in 1999 and quickly adapted to the new biotic and abiotic conditions (Brault, 2009; Reisen, 2013).

The global threat of mosquito-borne diseases to human health is counteracted by mosquito research and monitoring as important parts of integrated vector management in many countries. The World Health Organization (2012), continental and national authorities, such as the ECDC (ECDC, 2012, 2014) and the CDC (Center for Disease Control and Prevention, 2021), provide manuals and guidelines for native and invasive mosquito surveillance, but not all countries can follow due to financial or logistical restrictions (Impoinvil et al., 2007; Caputo and Manica, 2020). In this context, citizen science might be an approach to increase precision and cost-efficiency of mosquito monitoring and management by complementing the surveillance efforts of authorities (Bartumeus, Oltra and Palmer, 2018; Fouet and Kamdem, 2019). Indeed, mosquitoes seem to be a research object suitable for the masses: they appeal both to people who are interested in biodiversity and who are driven by health concerns. In addition, mosquitoes are known to almost everybody, because they bite, they buzz, and they are in general annoying for humans. Thus, the majority of people do roughly know how mosquitoes look like and have a strong emotional connection to these insects, both adequate prerequisites for a willingness to participate in respective citizen science programmes.

Therefore, the public has successfully been mobilised to participate in mosquito-related monitoring projects around the world, with different objectives, approaches, and scopes. In principle, large-scale (e.g. nationwide) projects rather focus on investigating and updating biodiversity and distribution, detecting new populations of invasive species, or assessing nuisance, such as the Dutch *Muggenradar*, the French *iMoustique* (Kampen et al., 2015), the Italian *ZanzaMapp* (Caputo et al., 2020), the *Mozzie Census* in New Zealand (Museum of New Zealand, 2020), or the *North American Mosquito Project* (Maki and Cohnstaedt, 2014). Smaller-scale projects follow more precise objectives, such as mosquito communities' responses to urbanisation, spread of one of the highly vector-competent *Aedes* species, or testing of new equipment and concepts. Examples include the originally Spanish but now pan-European *Mosquito Alert* (Oltra, Palmer and Bartumeus, 2016), regional short-term studies in the United States (Jordan, Sorensen and Ladeau, 2017; Johnson et al., 2018; Spence Beaulieu et al., 2019; Tarter et al., 2019), or the Australian pilot project *Mozzie Monitors* (Braz Sousa et al., 2020). Comparative studies with professional and citizen science data carried out in the context of some of these citizen science projects attest a similar or complementary data quality (Palmer et al., 2017; Braz Sousa et al., 2020). In the meantime, global efforts are being made to pool experience and tools of mosquito-related citizen science projects to make them available for volunteers and professionals worldwide (Tyson et al., 2015).

The German citizen science project 'Mückenatlas'

The citizen science project 'Mückenatlas' (German for 'mosquito atlas') is an integrated part of the national mosquito monitoring programme in Germany. Initiated in 2011, this programme started with conventional monitoring carried out by professionals, also referred to as *active monitoring*, as it involves trapping, netting and aspirating adults, and dipping for larvae, following a systematic procedure. This approach is associated with high costs for staff and equipment and at the same time limitations in time and sample sites. For this reason, *passive monitoring* has been complementing the professional data collection since 2012, in form of the citizen science project ‘Mückenatlas’ which addresses the public to support national mosquito mapping.

To participate in the ‘Mückenatlas’, everyone is invited to catch mosquitoes. Ideally, the mosquitoes are to be left undamaged, be killed by freezing, and sent to the involved institutes at own expense. A video and step-by-step description on the project’s website *www.mueckenatlas.com* explain in detail how to take part. A submission form is available on the website or through the project’s office for those lacking access to the internet, which shall accompany the mosquito(es) and in which date, location, and comments can be logged. Once the submissions have reached the institutes, sometimes bagful in summer (Figure 2, left), the catches are determined to species level and all information related to a catch is uploaded to the German culicid database.

Figure 2: During the mosquito high season, the ‘Mückenatlas’ receives hundreds of submissions per week (left). The website is the main communication tool of the citizen science project (right).

In return, every participant gets an answer (e-mail or letter) from the ‘Mückenatlas’ team with background information about the species sent and suggestions on how to deal with mosquito nuisance. To make their contribution public, participants can agree to their own location marker on the collectors’ map on the homepage of the project, which at the same time is a tool to browse through all submissions by year. In addition, the website is the main instrument of communicating research results, news on the project, and important media reports on citizen science and mosquitoes (Figure 2, right). Via a contact form, participants can contact the ‘Mückenatlas’ team directly.

Participants are mainly recruited through the media and sometimes through science events or word-of-mouth. As approachable experts, the project leaders are heavily involved in public relations work, so that reliable contacts with the public media have been established over the years. The project leaders are often consulted for media reports on invasive species, mosquito-borne diseases, or weather-related mass developments and then appeal to the public to participate in the 'Mückenatlas' at the same time. Thus, reports on television, in print media, and on the radio – nationwide, regional and local – as well as articles on the internet often refer to the project. This fruitful cooperation with the press, the simple participation procedure as well as the direct communication with the citizens are probably the main reasons why the 'Mückenatlas' has developed into one of the most successful and long-lasting citizen science projects in Germany. By June 2021, the project received over 150,000 mosquitoes out of more than 28,000 submissions.

The 'Mückenatlas' has not only contributed to the scientific output of the working groups involved, be it through the collected data or as a research object in itself, but has also been increasingly mentioned in external publications over the last few years (Figure 3).

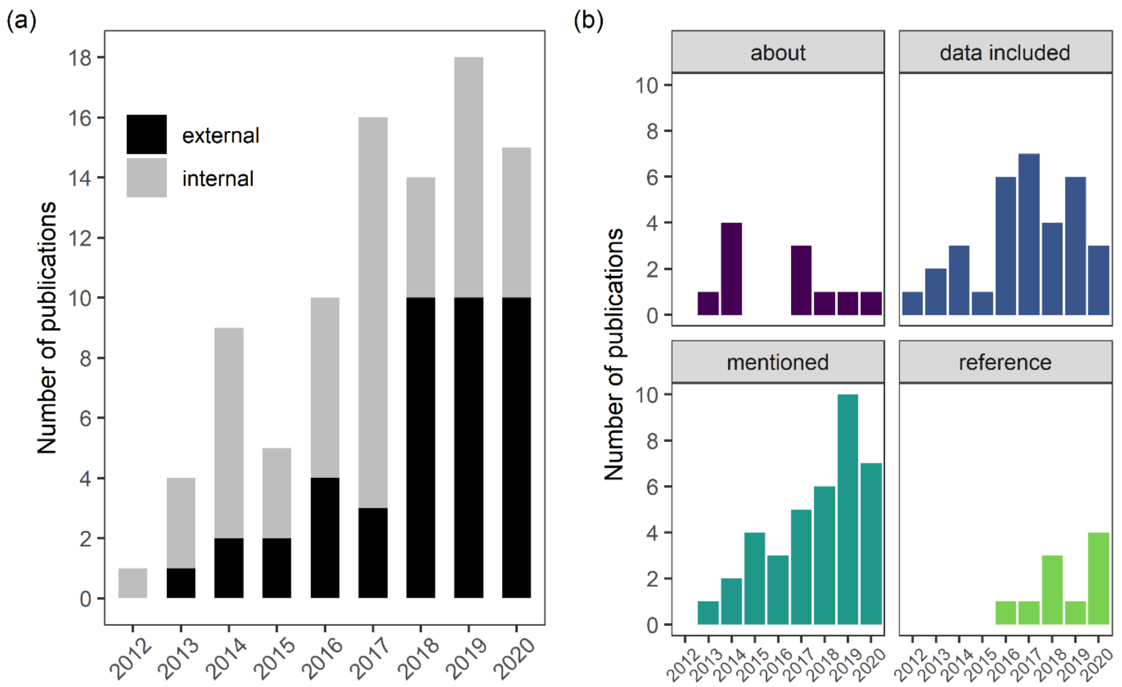

Figure 3: Publications in association with the 'Mückenatlas' based on a database search with the keywords 'Mückenatlas', 'Muckenatlas', 'Mueckenatlas' and 'mosquito atlas' in PubMed, Google Scholar, Web of Knowledge and Scopus on 18 February 2021, including journal articles, dissertations, book chapters, conference proceedings and scientific reports. (a) Total number of associated publications from 2012 to 2020 split up according to external (black) or internal (grey) origin. (b) Number of publications about the project itself (about), using 'Mückenatlas' data (data included), mentioning the project with at least one descriptive sentence (mentioned) and referring to the 'Mückenatlas' with a link or as literature reference (reference).

In combination with the information from *active monitoring*, the 'Mückenatlas' data provided valuable insights into species occurrences (e.g. Kampen et al., 2016, 2020; Kuhlisch, Kampen and Werner, 2019; Werner, Kowalczyk and Kampen, 2020), current and predicted distribution of invasive species (Kerkow et al., 2019, 2020), and population genetics (Zielke et al., 2014, 2015; Zielke, Walther and Kampen, 2016). Publications about the project and its achievements further enriched the scientific community at a time when the citizen science movement was increasingly getting attention in Germany (Hecker et al., 2014; Walther and Kampen, 2017).

1.5 Motivation and thesis objectives

The *science of citizen science* is still in its infancy. The motivation for this work was to advance the field by taking the unique opportunity to address a range of relevant issues through a single example, the 'Mückenatlas'. At the same time, since the launch of the citizen science project, its actual impact on national mosquito monitoring has not yet been scientifically studied. Coming from both directions, the aim of this work is to assess the contributions of the opportunistic data collection to mosquito research in Germany. For this, I have considered the 'Mückenatlas' from three different perspectives: as a monitoring method, as a data source, and as a public outreach activity. This selection was made because each perspective reflects a topic that is currently being controversially discussed and investigated in the discipline of citizen science.

As presented in the introduction, there is a variety of citizen science approaches to monitor biodiversity, but there are also knowledge gaps about how well they work. Therefore, the first work package, *Method*, addresses questions on the performance of the 'Mückenatlas' as an example of an unstructured citizen science programme: What did the project contribute to the production of knowledge on mosquitoes in Germany? What are its achievements in comparison to conventional monitoring methods? The second work package, *Data,* is dedicated to the controversies about the usability of citizen science data. It focuses on the questions: Are there temporal and spatial patterns in the submissions that can be attributed to anthropogenic and environmental factors? Are the data applicable for research despite these patterns? Lastly, publications on communication strategies in citizen science projects are sparse, especially on their impacts on the citizens' responsiveness, participation frequency and data structure. Therefore, the work package *Outreach* aims to investigate the association between 'Mückenatlas' communication activities and patterns of participation, specifically to determine how, when, and to what extent media activities affected the data collection process. In order to address these three work packages, different studies were carried out, which are summarised in Figure 4.

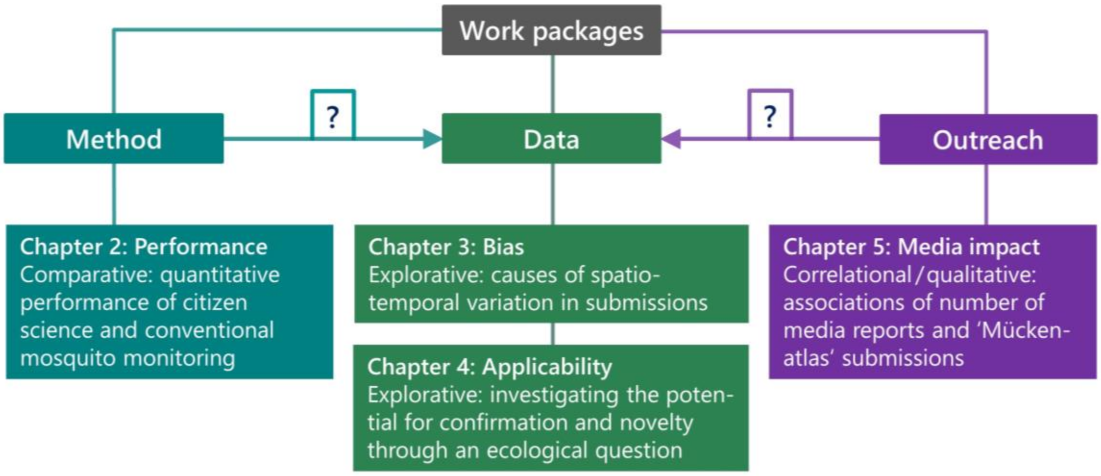

Figure 4: Overview scheme of the dissertation's work packages and resulting chapters. The question marks stand for potential impacts of *Method* and *Outreach* on the data structure, thereby linking the single work packages.

In the work package *Method*, the citizen science project is purely considered as an approach to monitor mosquitoes with the question of how far it contributes to the success of national mosquito monitoring, especially in terms of recording species. To assess the performance of the 'Mückenatlas' approach to mapping mosquitoes – as presented in Chapter 2 – the data collected by citizens (*passive monitoring*) were compared with professional sampling data (*active monitoring*). The coverage of land use types, species richness, and discovery curves as well as the capability of detecting invasive species of each approach were used as comparative values. In particular, weaknesses and strengths of *passive* and *active monitoring* were determined in order to make statements about the effectiveness of combining these two methods and recommendations on how to design a citizen science project for integration into formal mosquito monitoring programmes.

The two studies carried out in the work package *Data* address the characteristics of the opportunistic data collection. The biases and the explanatory power of the 'Mückenatlas' data was investigated to evaluate their applicability for mosquito research. Therefore, annual and monthly variation in submission numbers were examined in Chapter 3, looking for possible explanations by participant behaviour or climatic variations that could influence mosquito trends. In addition, potential drivers of spatial patterns were tested by applying models with pre-defined predictor variables known to induce biases in similarly large citizen science datasets. The study presented in Chapter 4 capitalises on one of the strongest advantages of citizen science by drawing on data that is normally inaccessible to researchers: most of the 'Mückenatlas' submissions come from the inside of private homes, providing a unique opportunity to investigate the indoor species diversity along a rural-urban gradient. In doing that, the data was simultaneously tested for their power to produce confirmative or novel insights into mosquito ecology.

The work package *Outreach* focuses on the citizen scientists, who not only provide important data for research, but are also sensitised to the relevance of mosquitoes for public health through the 'Mückenatlas' communication strategy. In this context, Chapter 5 explores the role of mass media to draw attention to the citizen science programme through a study on whether media presence of the 'Mückenatlas' affects participation or not. By means of a media clipping dataset containing records on television, radio, print, and online reports on the project, the number of submissions were correlated with the number of media reports featuring the 'Mückenatlas' over time and space. Since media coverage showed temporal and spatial patterns, associations between title and text quality on participant responsiveness were also investigated.

In the General discussion (Chapter 6), I bring together the individual findings of the four studies and their input to assess the contributions of the opportunistic data collection to mosquito research in Germany. In the concluding remarks I place the results of my research in a broader context and show what implications and recommendations can be derived for future citizen science projects. This includes a reflection of the potential and limitations of the 'Mückenatlas' approach for mosquito monitoring in particular and biodiversity monitoring in general. This dissertation will end with an outlook on possible future research on the topic.

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Chapter 2 | Citizen science versus professional data collection: Comparison of approaches to mosquito monitoring in Germany

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RESEARCH ARTICLE

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

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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 CO_2 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 GGPLOT2 (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-Sentinels. 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.

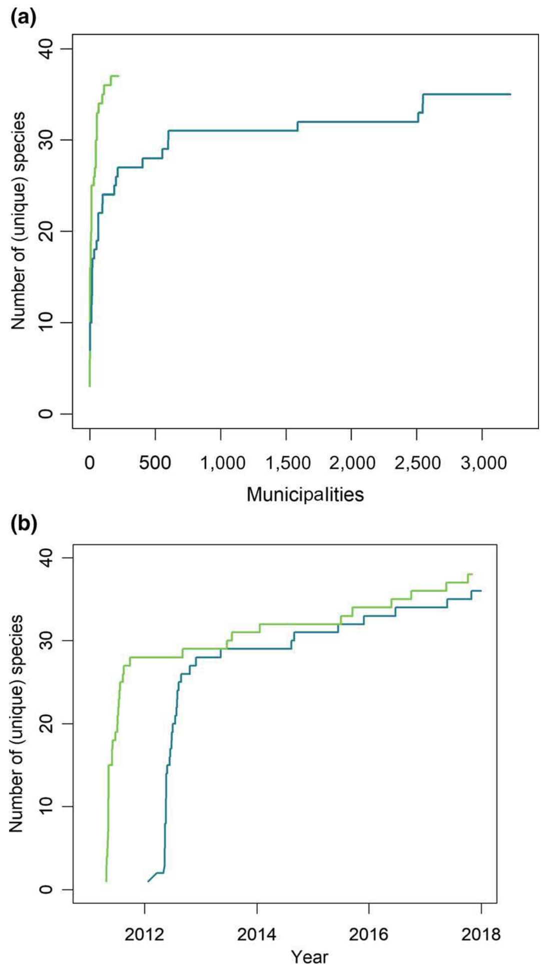

FIGURE 2 Species collectors curve, (a) over sites (municipalities), and (b) over time of active (green) and passive (blue) monitoring [Colour figure can be viewed at wileyonlinelibrary.com]

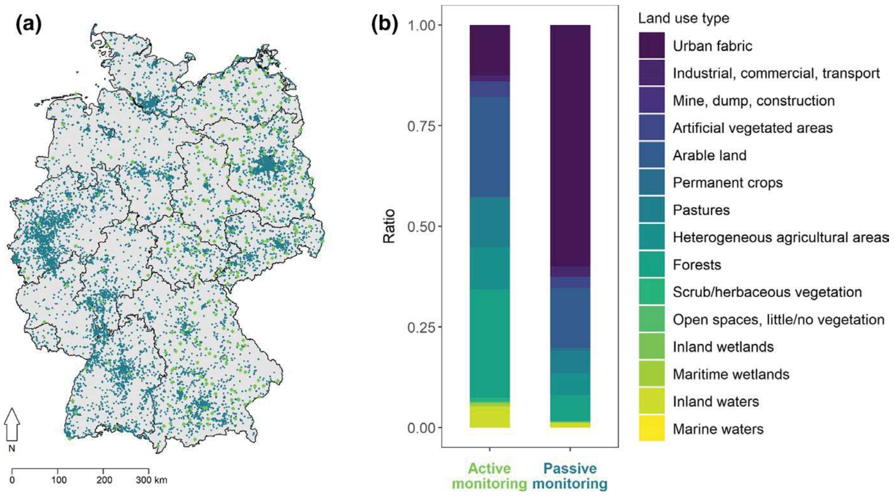

FIGURE 1 (a) Locations of BG-Sentinel traps (active monitoring: green points) and of 'Mückenatlas' submissions by citizen scientists (passive monitoring: blue points). (b) Land use type proportions of catch locations in active and passive monitoring datasets, broken down to CORINE level 2 [Colour figure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

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 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.

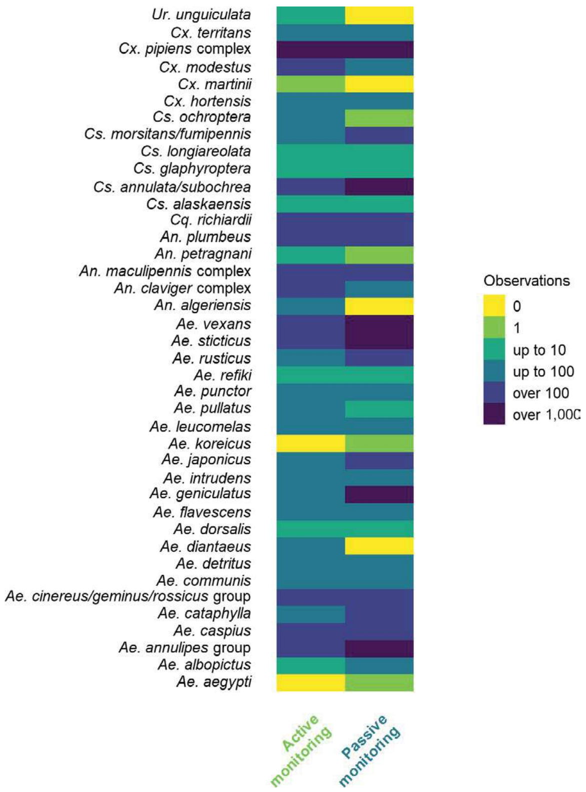

FIGURE 3 Species heat map of active and passive monitoring, showing the number of collected species by categories. *Species allocation: *Culex pipiens* complex: *Culex pipiens* including biotypes *pipiens* and *molestus*, *Culex torrentium*; *Aedes annulipes* group: *Aedes annulipes*, *Aedes cantans*, *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* [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Invasive species

Both methods detected *A. japonicus*, *A. albopictus*, *Aedes petragnani* 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

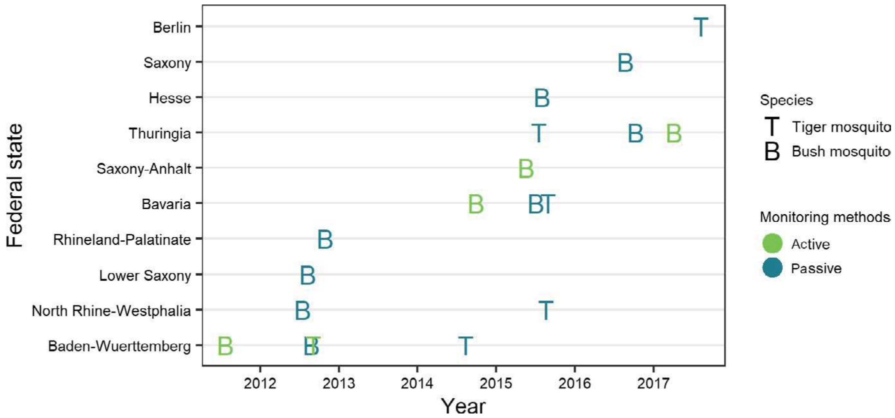

FIGURE 4 First records of *Aedes albopictus* (T; Asian tiger mosquito) and *Aedes japonicus* (B; Asian bush mosquito) in German federal states by active (green) and passive (blue) monitoring [Colour figure can be viewed at wileyonlinelibrary.com]

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 diantaeus*, *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 (Kuhlisch 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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SUPPORTING INFORMATION

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

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Appendix: Supporting Information Chapter 2

Table S1: Covariates that were (i) automatically exported by the CULBASE database and (ii) manually created for this study (these are highlighted in grey).

Variables	Explanation
Species code (specc)	Internal hierarchical key for species, numeric
Species name original (spec.o)	Species or - in not determinable cases - genus name, character
Species name adapted (specn)	Species names only, genus only set to NA
Species allocated (specgroup)	Species allocation to groups and complexes, genus only set to NA
Geo-reference (xvalue)	Geographical latitude, decimal in WSG1984
Geo-reference (yvalue)	Geographical longitude, decimal in WSG1984
Corine Land Cover Category code (coverc)	Corine Land Cover Category, numeric
Corine Land Cover Category name (covern)	Corine Land Cover Category Level 3, character
Corine Land Cover Category name (covern1)	Corine Land Cover Category Level 2, character
Corine Land Cover Category name (covcat)	Corine Land Cover Category Level 1, character
County name (countyn)	Federal state name, character
County code (countyc)	Federal state code code, numeric 1 to 16
Municipality name (munin)	Municipality name of nearest village to geo-location, character
Date (catchdate)	Date of catch, DD.MM.YYYY
Biotope original (bio.o)	Participant notion about find spot, character
Biotope category (biocat)	Participant notion about find spot categorised, character

Table S2: Complete species list

	Active monitoring 'BG-Sentinel'		Passive monitoring 'Mückenatlas'	
Species*	**n**	**%**	**n**	**%**
Ae. aegypti	0	0.00	1	0.00
Ae. albopictus	10	0.09	51	0.24
Ae. annulipes group	507	4.41	1106	5.11
Ae. caspius	175	1.52	178	0.82
Ae. cataphylla	77	0.67	208	0.96
Ae. cinereus/geminus/rossicus group	406	3.53	206	0.95
Ae. communis	60	0.52	21	0.10
Ae. detritus	12	0.10	19	0.09
Ae. diantaeus	28	0.24	0	0.00
Ae. dorsalis	6	0.05	2	0.01
Ae. flavescens	19	0.17	17	0.08
Ae. geniculatus	74	0.64	1341	6.20

Ae. intrudens	17	0.15	12	0.06
Ae. japonicus	35	0.30	893	4.13
Ae. koreicus	0	0.00	1	0.00
Ae. leucomelas	39	0.34	66	0.30
Ae. pullatus	12	0.10	5	0.02
Ae. punctor	96	0.84	94	0.43
Ae. refiki	5	0.04	2	0.01
Ae. rusticus	34	0.30	165	0.76
Ae. sticticus	277	2.41	1081	4.99
Ae. vexans	803	6.99	1999	9.24
An. algeriensis	32	0.28	0	0.00
An. claviger complex	331	2.88	75	0.35
An. maculipennis complex	578	5.03	493	2.28
An. petragnani	2	0.02	1	0.00
An. plumbeus	583	5.07	500	2.31
Cq. richiardii	434	3.78	701	3.24
Cs. alaskaensis	2	0.02	4	0.02
Cs. annulata/subochrea	623	5.42	3790	17.51
Cs. glaphyroptera	2	0.02	9	0.04
Cs. longiareolata	5	0.04	9	0.04
Cs. morsitans/fumipennis	100	0.87	112	0.52
Cs. ochroptera	42	0.37	1	0.00
Cx. hortensis	80	0.70	26	0.12
Cx. martinii	1	0.01	0	0.00
Cx. modestus	110	0.96	46	0.21
Cx. pipiens complex	5847	50.87	8382	38.72
Cx. territans	27	0.23	28	0.13
Ur. unguiculata	3	0.03	0	0.00
Total	**11,494**	**100**	**21,645**	**100**

* 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*.

Table S3: Absolute and relative numbers of CORINE Land Cover land use types.

		Passive monitoring 'Mückenatlas'		**Active monitoring 'BG-Sentinel traps'**	
CORINE Land Cover level-1 category	*CORINE Land Cover level-2 category*	*Level 1 %*	*Level 2 % (n)*	*Level 1 %*	*Level 2 % (n)*
Agricultural areas	Arable land	26.67	14.87 (3237)	47.78	24.74 (2888)
	Heterogeneous agricultural areas		5.35 (1165)		10.44 (1218)
	Pastures		5.73 (1247)		12.53 (1462)
	Permanent crops		0.72 (156)		0.08 (9)
Artificial surfaces	Artificial vegetated areas	65.29	2.67 (582)	17.94	3.94 (460)
	Industrial, commercial. transport		2.55 (554)		1.57 (183)
	Mine, dump, construction		0.16 (35)		0
	Urban fabric		59.91 (13041)		12.43 (1451)
Forest and semi natural areas	Forests	6.53	6.39 (1390)	27.96	26.87 (3136)
	Open spaces, little/no vegetation		0.04 (8)		0.05 (6)
	Scrub/herbaceous vegetation		0.11 (23)		1.04 (121)
Water bodies	Inland waters	1.24	1.20 (261)	5.57	5.31 (620)
	Marine waters		0.05 (10)		0
Wetlands	Inland wetlands	0.27	0.27 (59)	0.75	0.26 (30)
	Maritime wetlands		0		0.75 (88)

Chapter 3 | Drivers of spatio-temporal variation in mosquito submissions to the citizen science project 'Mückenatlas'

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Drivers of spatio-temporal variation in mosquito submissions to the citizen science project 'Mückenatlas'

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Intensified travel activities of humans and the ever growing global trade create opportunities of arthropod-borne disease agents and their vectors, such as mosquitoes, to establish in new regions. To update the knowledge of mosquito occurrence and distribution, a national mosquito monitoring programme was initiated in Germany in 2011, which has been complemented by a citizen science project, the 'Mückenatlas' since 2012. We analysed the 'Mückenatlas' dataset to (1) investigate causes of variation in submission numbers from the start of the project until 2017 and to (2) reveal biases induced by opportunistic data collection. Our results show that the temporal variation of submissions over the years is driven by fluctuating topicality of mosquito-borne diseases in the media and large-scale climate conditions. Hurdle models suggest a positive association of submission numbers with human population, catch location in the former political East Germany and the presence of water bodies, whereas precipitation and wind speed are negative predictors. We conclude that most anthropogenic and environmental effects on submission patterns are associated with the participants' (recording) behaviour. Understanding how the citizen scientists' behaviour shape opportunistic datasets help to take full advantage of the available information.

Mosquito-borne diseases pose an increasing threat to human and animal health worldwide. Human-mediated dispersal, for example by global trade or travelling, are the main factors for the introduction of non-indigenous species such as the Asian tiger mosquito *Aedes albopictus* or the yellow fever mosquito *Aedes aegypti*[1,2]. Due to their adaptability and potentially facilitated by global warming, both species have succeeded in establishing populations in new regions[3,4], and are potential vectors of a range of pathogens such as dengue or chikungunya viruses[1]. Comprehensive, long-term data collection about the distribution and phenology of invasive as well as native species that are competent vectors of pathogens[5] are required to prevent infections, to assess and decrease impacts on human and animal well-being and to predict how particular vectors will spread.

To collect and update data as a basis for risk assessments, the German government initiated a still ongoing nationwide mosquito monitoring programme in 2011, consisting of targeted field efforts by scientists and a complementary citizen science project. While developmental stages and adults have been actively collected by dipping and trapping throughout Germany since the start of the programme[6], this kind of professional monitoring is limited by staff and funding and can only provide snapshots of mosquito populations in selected habitats. Moreover, lack of access to private properties and of data from the people's immediate surroundings, where, for example, invasive species readily breed in artificial containers, hampers risk assessments. The importance of such data from densely populated areas is illustrated by the first West Nile virus infections in Berlin in 2019[7]. To enhance data collection and to complement active surveillance by scientists, the citizen science project 'Mückenatlas' (mosquito atlas) started in 2012. Contrary to the majority of biodiversity monitoring projects involving citizens and working with online recordings via a website or an app, for instance *eBird*[8] and *iNaturalist* on a global or the Spanish *Mosquito Alert*[9] and the Austrian *RoadKill*[10] on a national scale, 'Mückenatlas' participants do not upload

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records or are involved in the identification of the reported specimens themselves. Instead, they catch and send physical samples that are then determined to species level by the project's experts according to a standardised protocol[11]. In this way, the 'Mückenatlas' has the benefits of citizen science—large observation numbers and a large geographic scale—while taking a rather conservative approach to ensure data quality instead of controlling for data quality issues with tools such as crowdsourcing, external expert validation or in-process data vetting[8,9].

Another advantage of opportunistic sampling by citizens is to increase the probability of detecting rare or unexpected events, such as the arrival of an invasive species or the return of a particularly rare taxon[12]. With regard to mapping biodiversity and detecting invasive species, the 'Mückenatlas' has already attested its efficiency: submissions revealed new populations of *Aedes japonicus* (Asian bush mosquito) and *Ae. albopictus*[11,13–17], produced first records of *Ae. aegypti* and *Aedes koreicus* in Germany[18,19], and led to the rediscovery of very rare species after decades without documentation[20,21].

On the flipside, random collections from citizens result in opportunistic datasets incorporating observation bias caused by recorder activity[22] that vary in intensity depending on project design. Consequently, only small, species-specific fractions of the growing 'Mückenatlas' dataset have been analysed so far, e. g. to describe particular species findings[23], to investigate nuisance sources[24] or for population genetics[25]. Kerkow et al.[26], for example, mitigated bias by combining 'Mückenatlas' observations of *Ae. japonicus* with conventional monitoring data to predict species distribution, to some degree discussing patterns resulting from biases of both—in this case over- and underrepresentation of land-use types. Other case studies of observation patterns focus on intrinsic and extrinsic motivations of citizen scientists[27,28], less commonly on general environmental or anthropogenic factors associated with volunteers' recordings for large-scale citizen science projects[29,30]. Analysing these driving factors, however, would help utilise opportunistic data collections to full extent and design future citizen science projects.

The 'Mückenatlas' submissions have so far neither been explored nor evaluated from a citizen science perspective[31,32]. This study contributes to our knowledge about the complexity of submission patterns for long-term, large-scale citizen science projects with the particularity that, in contrast to other studies, there is no uncertainty concerning species identification. After the 'Mückenatlas' has been operating for more than seven years, we here aim at answering the following three questions: (1) Which trends and characteristics shape the opportunistic dataset? (2) Which factors drive the seasonal and annual variations in submission numbers? (3) Which factors drive the spatial distribution of submissions? These questions are tackled by a descriptive analysis of the dataset and by deploying hurdle models to test the association of several anthropogenic and environmental predictors with submission numbers.

Methods

'Mückenatlas' workflow. Citizens are asked to catch mosquitoes in a closable container without physically damaging them, and to kill them by freezing for at least 24 h. A form that can be downloaded from the project's website (http://www.mueckenatlas.com) and is also available at the project's office must be completed with information about the catch. The participants then send their catch along with the submission form to the project's laboratory where the sample is identified to species level morphologically[33,34] or, in difficult cases, such as damaged specimens or cryptic species, genetically[35]. As a reward, every participant receives a personal letter or email including detailed information about the submitted mosquito(es). If desired, the participants also get a mark with their name or a pseudonym on the website's collectors' map. The data corresponding to the catch is uploaded to CULBASE, the German mosquito database.

Data preparation. Data attributed with 'MA' (tag for 'Mückenatlas') were extracted from CULBASE on July 31, 2018, marking the end of the period of data entry for 2017. Each entry represents the submission of one or more specimen of one mosquito species from one location. We ignored specimen counts for this study as we focused on investigating submissions, irrespective of the exact number of specimens sent. The dataset consisted of a partly automatically generated suite of covariates composed of information from the submission form and database processing such as species, geo-coordinates, collection date and land-use types according to CORINE Land Cover data level 3[36]. Furthermore, the collection site description provided by the participants on the submission forms were categorised to a biotope variable. When information on the catch location was missing, the home addresses of the participants were taken as geo-coordinates by default, but no biotope category was assigned to the corresponding entries. Unclear site descriptions, such as 'hedge' or 'path' with geo-coordinates, as well as interpretable descriptions without geo-coordinates, such as 'forest nearby home', were verified manually by Google Maps. If the catch location could not be verified, biotope category was set invalid. In total, the resulting dataset comprised 21,768 submissions and 15 covariates (Supplementary Table S1). Explorative and descriptive analysis of the covariates to depict submissions and identify temporal trends were conducted with R packages *ggplot2*[37], *treemap*[38] and *summarytools*[39] deploying R version 3.5.2[40].

Raster data. To implement submission numbers as response variable for statistical testing, we drew a raster grid with a 5 km resolution across Germany and counted submissions in every grid cell to create a submission-distribution raster file. Over 73% of the grid cells showed zero submissions, and the frequency distribution was highly skewed to the right (Fig. 1).

We selected four environmental and four anthropogenic predictors per grid cell a priori (Table 1, Supplementary Fig. S1), which were considered candidates to explain the variability of submission distribution and numbers. Predictors were integrated as spatial raster values according to the response variable's raster extent. The variable 'population' was chosen because numerous previous studies in citizen science data have shown a strong positive relationship between total human population and the number of records[29,30], and we expected the same for our data. The two variables 'mean age' and 'proportion of women' were used to test patterns in participant

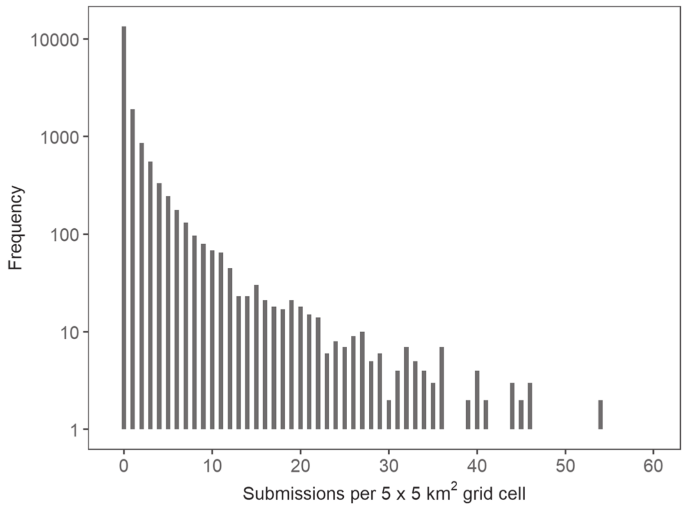

Figure 1. Histogram showing the numbers of grid cells on a log-transformed y-axis against the numbers of submissions per grid cell (limited to 60).

Anthropogenic variable	
Population (pop)	Human population in 2011 within each grid cell
Population age (age)	Mean age of human population within each grid cell in years
Proportion of women (fem)	Mean proportion of women within each grid cell in percent
Region (east)	Grid cell within the federal states located in former political East Germany (0 = no, 1 = yes)
Environmental variable	
Temperature (temp)	Mean temperature for March to November 2012 to 2017 in °C
Precipitation (preci)	Mean precipitation for March to November 2012 to 2017 in mm
Wind speed (wind)	Mean wind speed 10 m above ground 1981 to 2000 in m/s
Presence of water (water)	Standing water bodies, floodplains or wetlands in grid cell (0 = no, 1 = yes)

Table 1. Set of variables pre-selected as predictors.

engagement according to demographic background. This selection builds on studies with partly contradictory results which have investigated the age structure and gender of citizen scientists[41–44], giving us the idea of uncovering large-scale trends through spatial analysis rather than through sociological and selective participant surveys. As a fourth anthropogenic predictor, we created a binary variable that assigned the grid cells to former political East or West Germany in order to investigate whether the project headquarters' locations—both based in federal states located in former East Germany—might affect the engagement of citizens and to test for general and large-scale differences in demographic structure and climatic conditions. We selected the environmental predictors that are generally important for the development and occurrence of the vast majority of mosquito species. These include precipitation, temperature, wind speed and natural water bodies that might be suitable for mosquito breeding[33]. For the latter we used open hydrographical data from a Web Feature Service (WFS)[45] of a range of hydrological landscape features and included stagnant waters as well as floodplains and wetlands as areas presumably suitable for larval development. The preference for a binary variable over a numeric one or, in other words, whether or not there is a water body in the grid cell in favour of percentage coverage, was based on the assumption of a strong, positive correlation of the number of water bodies with submission numbers. Percentages would lead to meaningless associations due to the nature of the project, e.g. a 100% coverage of the grid cell with water would correlate with a maximum number of submissions, although no potential participants could live there. Wind speed turned out to be an interesting environmental factor in previous studies on predicting mosquito spread[26], as it induces flight restriction and therefore decreases the probability of a mosquito to be caught. For example, *Ae. japonicus* has not yet been detected in German areas with an average wind speed > 4.7 m/s, based on results from both passive and active surveillance schemes[26]. Data on human population, mean age and proportion of women were derived from the German census in 2011[46], while the German Weather Service[47] (Deutscher Wetterdienst Climate Data Center) provided data on mean wind speed (1981–2000) as well as on mean temperature and precipitation for March to November, from 2012 to 2017, to describe the climatic conditions during the mosquito seasons.

The predictors were grouped into anthropogenic and environmental factors. This allowed us to consider (1) the participants as a driving factor for submissions and (2) the effect of environmental variables on the occurrence

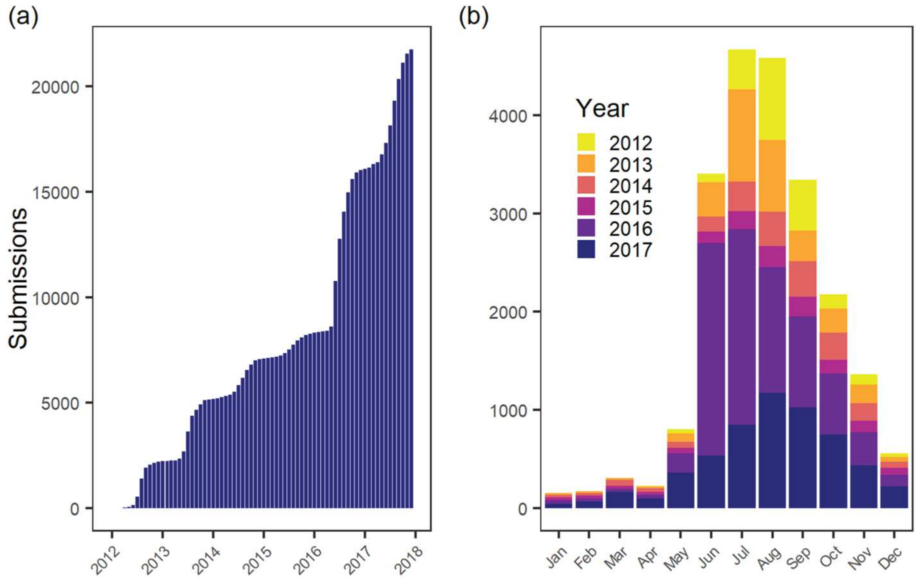

Figure 2. Temporal variation in submission numbers. (**a**) Cumulative submission numbers from 2012 to 2017. (**b**) Total number of submissions per month over all study years.

of mosquitoes. However, this is a simplification of the ecological interactions of the underlying complex network, as every predictor might influence both participation behaviour and mosquito occurrence. For example, high wind speed might not only prevent mosquitoes from flying but also people from collecting mosquitoes outside, whereas a dense human population also provides a variety of habitats and hosts for container-breeding mosquitoes. Raster files of response variable and predictors were built with packages *sf*[48], *leaflet*[49], *raster*[50], *rgdal*[51] and *spatstat*[52].

Statistical analysis. Predictors were applied to fit hurdle models using either the probability of a zero count (binomial) or the number of submissions per grid cell (truncated negative binomial), accounting for over-dispersion and excess zeros in the data. Multicollinearity was checked by calculating variance inflation factors (VIF) and, consequently, the predictors 'mean age' and 'temperature' with returned values > 5 were removed. The hurdle models allowed us to examine whether a certain set of predictors has an effect on (1) the probability of a non-zero count in the zero and (2) the number of submissions in the count part. All possible combinations of predictors were explored for both modelling parts using Automated Model Selection (AMS; command *dredge* in R package *MuMIn*) that ranks models by AIC and Akaike's model weight. Models were selected and realised by the R packages *car*[53], *countreg*[54], *MuMIn*[55], *MASS*[56] and *pscl*[57].

Ethical approval. Ethical approval was not required because the collected data were anonymised, location data were aggregated and further processed without geo-referencing. The use of personal data complies with the EU General Data Protection Regulations; no personal sensitive information was obtained during this project or shared outside of the research team.

Informed consent. Insect samples were provided voluntarily by citizen scientists after consent was given to the processing of the sender data according to EU General Data Protection Regulation.

Results

Characteristics of and temporal variation in submissions. Between January 23, 2012 (first submission to 'Mückenatlas') and December 31, 2017, a total of 21,768 submissions from 11,277 locations (geo-coordinates) in 3221 municipalities were received. The number of specimens sent to the 'Mückenatlas' in the above time period adds up to 110,581; 3950 additional samples of arthropods submitted did not belong to the family *Culicidae* and were excluded from the study. Some submissions included several hundreds of specimens of the same species. This explains the difference between number of submissions recorded in the database and total species count, as we only created one CULBASE entry per species and submission, independently of the count which is recorded as a covariate. 2016 and 2017 represent the most productive years with 7756 (35.6% of all submissions from 2012–2017) and 5730 (26.3%) submissions, respectively, with June 2016 holding the monthly record of 2163 (9.9%) submissions (Fig. 2a). When submissions are added up according to month for the total observation period, most mosquitoes were submitted in July (4674, 21.5%), followed by August (4583, 21.1%), June (3405, 15.6%) and September (3341, 15.4%). The autumn months October and November still exhibit over 1000 submissions each, and are followed by a considerable decline during winter and spring, before submission numbers rise again in May (Fig. 2b).

Figure 3. Proportional treemap of categorised participants' biotope information showing the overrepresentation of submissions from private surroundings. Only biotopes with portions ≥ 1.5% are presented individually, categories with a smaller share have been combined into 'other'. Plotted with package *treemap* in R version 3.5.2.

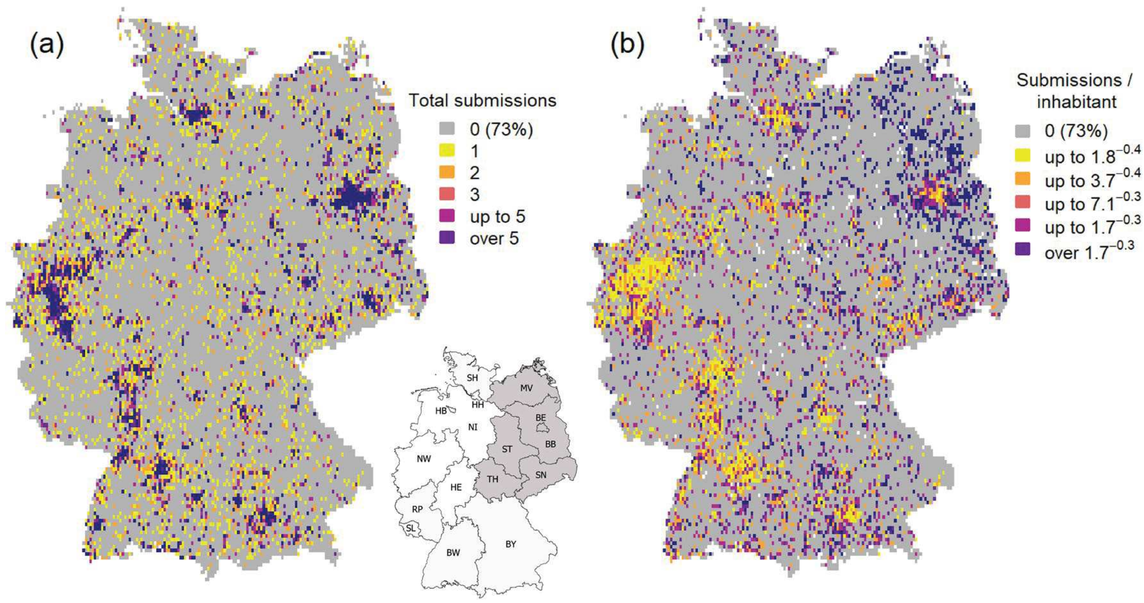

Figure 4. Federal states of Germany (*SH* Schleswig-Holstein, *HH* Hamburg, *HB* Bremen, *NI* Lower Saxony, *NW* North Rhine-Westphalia, *HE* Hesse, *RP* Rhineland Palatinate, *SL* Saarland, *BW* Baden-Wuerttemberg, *BY* Bavaria, *MV* Mecklenburg Western-Pomerania, *BB* Brandenburg, *BE* Berlin, *ST* Saxony-Anhalt, *SN* Saxony, *TH* Thuringia). (**a**) Raster grid of Germany (5×5 km^2 cell size) of total submission numbers. (**b**) Raster grid of Germany (5×5 km^2 cell size) showing per-capita submission rates (white grid cells = zero submission and zero/invalid population data). Both raster maps were created in R version 3.5.2., the German map outlining the federal states was drawn using QGis version 3.4.2. (Quantum GIS Geographic Information System, Open Source Geospatial Foundation Project. http://www.qgis.org/en/site/).

Almost every participant (92.9%, not applicable = 7.1%) provided information about the collection site, so that biotope descriptions could be considered during data analysis. According to the CORINE Land Cover Data level 3, most mosquitoes were caught in 'discontinuous urban fabric' (12,718, 58.4%), 'non-irrigated arable land' (3237, 14.9%) and 'pastures' (1247, 5.7%). In agreement, the most frequent specification of the collection sites as provided by the participants were 'home indoors' (13,305, 66.4%), followed by 'home outdoors' (e.g. garden, backyard, court; 3446, 17.2%) and 'intersection home indoors/outdoors' (e.g. house walls, windows, entrance doors; 839, 4.2%) (Fig. 3).

Engagement hotspots in submission distribution. We further investigated the effect of 'population', as the map of total submission numbers strongly resembles a German human population map (Fig. 4a), with grid cells in densely populated areas, such as Berlin, Hamburg, Munich, the Ruhrgebiet and the Main-Neckar area displaying extremely high submission numbers. To disclose regions with high engagement independently of human population, we calculated a raster with per-capita submission rate, defined as number of submissions

Count hurdle model predictors (truncated negbin with log link)	Zero hurdle model predictors (binomial with logit link)	Delta-AIC	AIC weight
+ pop + east + water – preci – wind	+ pop + east + water + fem – wind	0	0.328
+ pop + east + water (+ fem) – preci – wind	+ pop + east + water + fem – wind	0.055	0.319
+ pop + east + water – preci – wind	+ pop + east + water + fem (+ preci) – wind	1.320	0.170
+ pop + east + water (+ fem) – preci – wind	+ pop + east + water + fem (+ preci) – wind	1.374	0.165

Table 2. Best ranked models according to Akaike's model weight (cumulative AIC weight > 0.95). Each of the algebraic signs indicates a positive or negative association of predictors (pop = human population, east = binary, region of former political East or West Germany, water = binary, presences of stagnant water bodies, fem = proportion of women, preci = mean precipitation (March to Nov, 2012 to 2017), wind = mean wind speed (1981 to 2000) with submission numbers. In brackets: predictors not present in all of the best models.

per person, based on the total human population in the respective grid cell. The resulting map (Fig. 4b) exhibits a considerably higher per-capita submission rate for eastern and south-eastern regions with a core area around the capital of Berlin, whereas the western part of the country stands behind. Although ranking first in absolute submission numbers (3119, 14.3%), the federal state of North-Rhine Westphalia as the most densely populated German region results in a low per-capita submission rate. People from Brandenburg (3075, 14.1%) and Bavaria (2917, 13.4%), both less densely populated federal states, participate more often, with a peak of 250 submissions in one of the two project's hometowns, Müncheberg in Brandenburg (population: 6783), located approximately 50 km east of Berlin. To check if these hotspots are due to urban dwellers making trips to these areas rather than local residents, an additional analysis with entries coming exclusively from the participants' homes or gardens was conducted. The corresponding map (Supplementary Fig. S2) shows that the hotspot density becomes weaker, indicating that indeed some participants seem to be travelling from urban to rural areas to catch mosquitoes. Nonetheless, the pattern of greater involvement in the above-mentioned residential areas remains.

Distribution patterns by hurdle models applying anthropogenic and environmental predictors. The engagement hotspots suggest that the non-random distribution of submissions might also be caused by further anthropogenic and environmental variables, whose associations were therefore tested using hurdle models. A predictor was considered important when included in the four best ranked models based on the Automated Model Selection (AMS) with an accumulated AIC weight > 0.95 (Table 2). As expected from the previous analysis on engagement hotspots, the number of people living in a grid cell has an effect on both whether there is a submission and how many. Indeed, 'population' is included in both parts of the best 995 models (24.9%) calculated by AMS (Supplementary Table S2 for complete AMS output). 'Region' (East or West Germany), 'presence of water bodies' as well as 'wind speed' were also meaningful predictors of both submission numbers and submission probability. The importance of proportion of women and precipitation differs for each part of the hurdle models. Precipitation negatively affects the number, but not the probability of submissions. Conversely, the proportion of women in a grid cell may increase the probability of a submission from that unit, but does not influence record numbers.

To further explore relationships between predictors and response variables, we plotted the predictor values against the submission counts (Fig. 5). In accordance to model output, the resulting plots show a positive effect of human population and proportion of women on recordings, whereas increasing mean precipitation and mean wind speed per grid cell result in fewer submissions. The plots for mean age and mean temperature, both excluded from modelling due to multicollinearity, suggest a slightly and strongly positive association with submission numbers, respectively.

Discussion

With the tremendous and continuous numbers of mosquito submissions received between 2012 and 2017, the 'Mückenatlas' is one of the most popular and successful citizen science projects in Germany. For the first time, we analysed the underlying dataset to characterise the origin and structure of the submissions, to reveal major spatial and temporal trends in submission numbers and to investigate what might drive these patterns.

The main characteristics of the data are the overrepresentation of indoor samples from the participants' homes off densely populated areas. As shown in previous studies summarising popular citizen science projects focused on arthropods[58,59], the 'Mückenatlas' participants seem to be genuinely interested in arthropods present in and around their homes. This interest is not confined to mosquitoes, as the participants' messages on the submission forms indicate that the roughly 20% non-mosquito samples might be sent on purpose when people fail to identify a species they are curious about or suspect to be a pest. Such behaviour substantiates the high potential and success of large-scale and cross-taxonomic citizen science projects such as *iNaturalist* and supports the idea of a global community of citizen scientists recording species around their homes[60].

It is of advantage to receive specimens found in the direct neighbourhood of people, as private properties are not directly accessible for scientists and at the same time highly important for research[60]. From a public health point of view submissions from people's homes are of greater epidemiological relevance when addressing (arthropod-) vector-borne diseases[61] than rare species in non-inhabited areas; the latter are more valuable for biodiversity research[31,62]. From a data science perspective, the over- and underrepresentation of certain

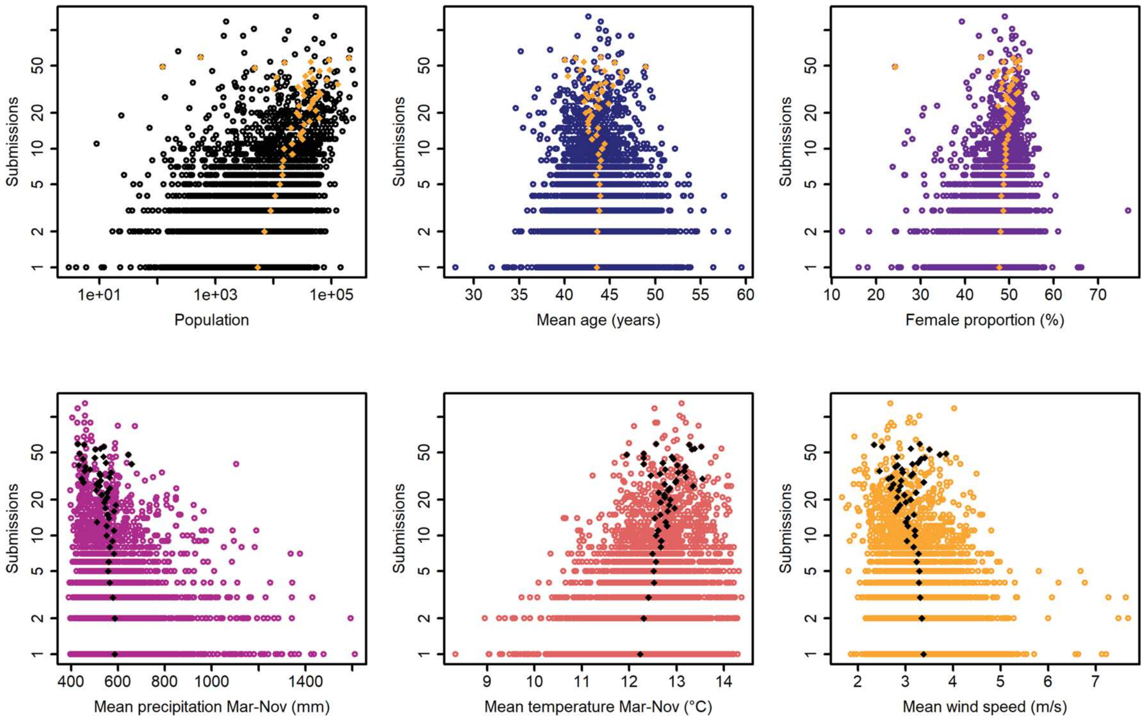

Figure 5. Scatterplots of the six non-factor predictors plotted against the number of submissions on a log-transformed y-axis. In the case of 'population', both axes are log-transformed. The yellow and black diamonds indicate average values per submission frequency.

land-use types create a spatial bias in the presence-only data to be considered when it comes to species distribution modelling[26,29,63].

Our analysis to identify temporal trends revealed a noticeable variation in submission numbers over the years and months. The boost in submission numbers in 2016 may be the result of an increased public awareness of mosquito-borne diseases[64], caused by an extensive flood of news about the South-American ZIKA virus epidemic, possibly triggering the maximum of recordings in June 2016 and sustained high numbers into 2017. We believe people became worried about mosquitoes in their living environment and—in a way of self-provisioning—approached the 'Mückenatlas' as an authority that could dissipate their concerns. In addition, the warm and humid weather in both 2016 and 2017 created beneficial conditions for many mosquito species in large parts of the country. This favourable climatic situation combined with the continuing public attention fuelled by the media may have kept the submission numbers high until the end of 2017. Temporal variation in citizens' observation records can confirm[65] or extend[66] findings on the phenology of the target species. In our case, the records even reflect those mosquitoes that enter people's homes in October and November to find an overwintering place, such as *Culiseta annulata*.

Based on the hurdle models we demonstrated how anthropogenic and environmental predictors relate to the spatial distribution of submissions. The positive correlation of human population with submission numbers was expected, especially since the visualisation revealed a spatial pattern of urban clusters known from other citizen science projects[29,30]. After controlling for the influence of human population, engagement hotspots became apparent in East Germany, predominantly in the sparsely populated federal states of Brandenburg and Mecklenburg-Western Pomerania[67]. This finding is corroborated by the models' estimated positive association of the predictor 'east' with submission numbers. In other words, a location in former East Germany increases the number and probability of submissions. We attributed this trend to the project's institutional homes in Brandenburg and Mecklenburg-Western Pomerania: frequent regional media coverage and participation in regional (science) events may create a *headquarter effect* that leads to a strong project support and identification by local communities. Newman et al.[68] discovered that place-related effects play a considerable role in citizen scientists' motivations to participate, especially in programmes using volunteer data for conservation decisions. This 'power of place'[68] may even present a stronger driver for participation than citizen concerns about invasive species: of the regions invaded by *Ae. japonicus* and *Ae. albopictus*, only the infested Southwest showed an increased engagement.

Considering the third investigated anthropogenic effect included in the models, a higher proportion of women per grid cell positively affects participation, but only the odds of a submission, not the number of submissions. However, it would be premature to conclude that women are more likely to contribute to the 'Mückenatlas'. Much more information is needed to test associations of submissions with the participants' demographic background, for instance to check if this weak positive correlation is due to the female surplus in urban areas.

Our model estimates imply that submission numbers could partly reflect environmental conditions. The presence of water is one key factors of mosquito development and occurrence[33], suggesting the positive correlation for both model parts may not only be due to a higher probability of encountering mosquitoes near breeding habitats, but also in larger numbers. The prevalence of water bodies in the north-eastern part of Germany might further contribute to the stronger engagement in this area, where—contrary to other regions with similar landscape features[69]—management actions are not carried out (e.g. large-scale application of *Bacillus thuringiensis israelensis* by helicopter along sections of the river Rhine).

Of the environmental variables that negatively relate to the number of submissions, wind speed affects both the number and probability of submissions, because the absence or inactivity of mosquitoes in breezy coastal or mountainous regions is likely to result in few mosquito encounters. More surprising is the inverse correlation of precipitation with only submission counts, as mosquito breeding depends on the availability of water, with small natural sites such as tree holes or small ponds strongly prone to desiccation. Yet most submissions came from people's private surroundings, houses or gardens, and therefore from areas that could have persisting water sources independent of precipitation. People inadvertently tend to create perfect mosquito habitats by garden design and irrigation, and the topmost mosquito taxa submitted to the 'Mückenatlas' (*Culex pipiens* complex, *Cs. annulata* or *Ae. japonicus)*, readily breed in garden ponds and in a range of artificial containers such as water-filled rain barrels, flower-pot dishes, vases or bird baths[70,71]. The exclusive association of precipitation with submission counts again indicates a possible relationship with engaged communities in the north-eastern part of Germany, where precipitation is lower compared to the rest of the country[72].

We aimed at reflecting mosquito seasonality by calculating the overall mean of precipitation (and temperature) from March to November for the years 2012 to 2017. While adequate for a first exploration of driving factors as conducted in this study, this simplification would be insufficient and inexact for predicting submission numbers, given the likely influence of climate on their temporal variation (as already discussed). Instead of using the standard approach with weather variables like seasonal means, modelling the distribution of submissions and also of species, could be improved by variable decomposition to allow for inherent spatio-temporal fluctuations as well as for anomalies[73], which would be especially useful to account for the phenology of semi-aquatic arthropods like mosquitoes.

Conclusions

The 'Mückenatlas' is an analogue citizen science project open to everyone, without any preparation or constraints like collection kits, educational training or sampling protocols. This study lays the foundation to future applications of this specific opportunistic dataset that does not struggle with data quality, but displays massive spatio-temporal variation in citizen submissions of mosquito samples. Although environmental factors do play their part in spatio-temporal variation of 'Mückenatlas' submissions, it is the citizens and their recording activities that primarily shape the data.

Our findings have five important implications for (mosquito-related) citizen science monitoring projects. First, an unstructured, opportunistic programme such as the 'Mückenatlas' is well suited to collect data from several taxa over a long period of time and over a large area in order to mitigate uncontrollable effects such as climate variability, which, in the case of mosquitoes, strongly influences their occurrence and abundance. In contrast, studies on a smaller spatial scale, for specific species or habitats, or over a shorter period of time, would benefit from a structured approach to better anticipate the spatio-temporal effects of environmental factors through sampling protocols or pre-selection of place and time.

Second, the main anthropogenic causes of spatial bias in opportunistic data collections are human population and the preference of citizens to take part in projects that allow data collection at home or close by[74]. Citizen science monitoring programmes can prepare for this urban clustering and overrepresentation of observations from artificial surfaces by adapting protocol design and regulating the recruitment of participants (e.g. by creating sample units with fixed numbers of participants), by clearly defining their research questions and project goals, and by developing strategies for appropriate data analysis[75,76].

Third, more engaged communities cause spatial bias, but these location-based effects could also be used to the advantage of the project, e.g. in the case of mosquito-related citizen science projects to tap local knowledge about mosquito abundance[77].

Fourth, due to their impact on human health and well-being, mosquitoes are a regular media topic in many countries. The rush for the 'Mückenatlas' in 2016, probably triggered by the ZIKA epidemic, demonstrate the influence of the media, but also emphasise the usefulness of media for citizen science, whether for general recruitment, as a specific appeal for a particular region (e.g. on the frontline of an invader's spread) or to draw attention to certain species of scientific interest. Eritja et al.[78] used the media and place-based effects to activate the local community to search for *Ae. japonicus* after a first record in northern Spain.

Finally, if the data situation is suitable, a hurdle model can be used to test if certain variables influence the number and/or probability of an observation. This could be done, for example, in the improvement or planning of citizen science projects, e.g. by taking additional, more targeted measures to recruit from areas for which the model predicts low participation. By including demographic information, we tested the applicability in large-scale spatial modelling in the context of citizen science. Although the approach is promising for identifying bias caused by national demographic trends, it cannot replace the accuracy of a social science survey of participants. For example, it would then also be possible to find out whether stronger regional engagement is associated with the attitude towards participatory formats of former citizens of East versus West Germany.

This study and many existing and emerging citizen science projects show that the public can provide valuable support in monitoring biodiversity, also of arthropod vectors, but there is still great potential to develop methods to improve data robustness.

Data availability

For the time being, the raw data used for this study cannot be provided publicly, as the geo-references are connected with the participants' home addresses. Sharing the raw data would violate the personal privacy of the citizen scientists. However, the subset of spatial data (raster) used for modelling submission counts 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.153.

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Author contributions
N.P. conceptualised the work, analysed and interpreted the data and prepared a draft of the manuscript. F.R. contributed to data analysis, interpreted the data and revised the manuscript. J.M.J. provided advice, interpreted the data and revised the manuscript. H.K. and D.W. designed the study, raised funds, provided the data, interpreted the data and revised the manuscript. All authors contributed critically to the manuscript drafts.

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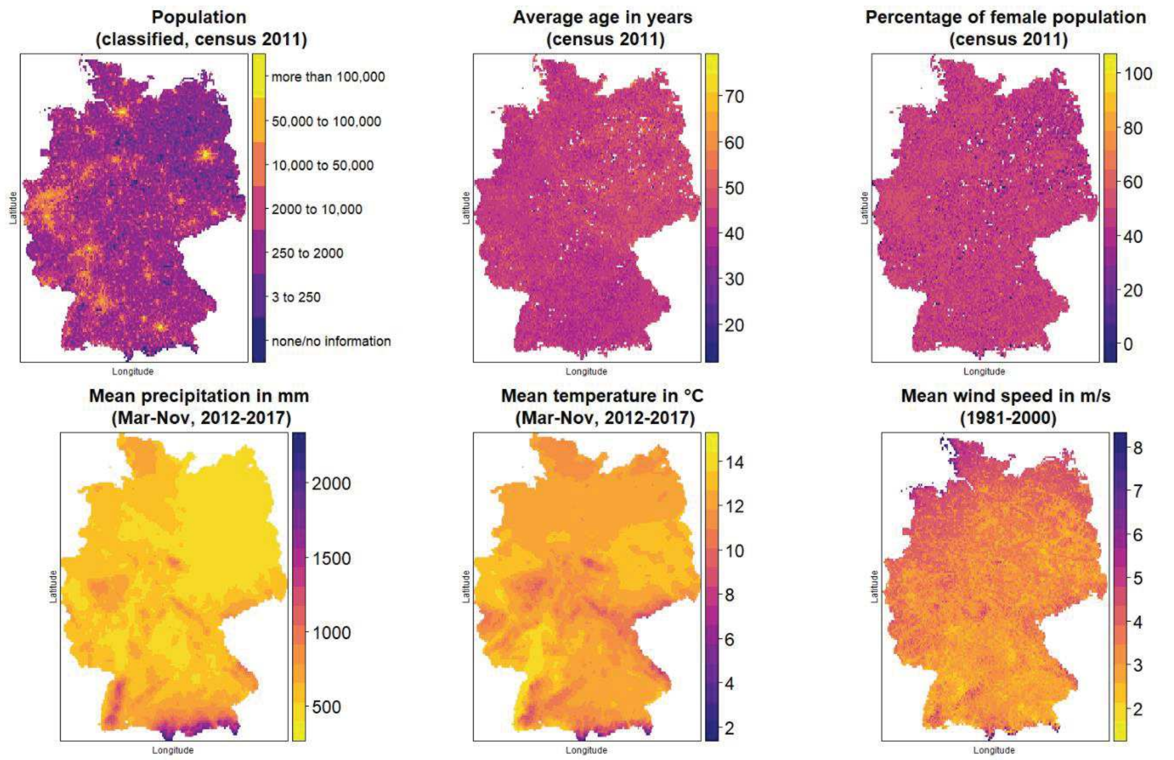
Appendix: Supporting Information Chapter 3

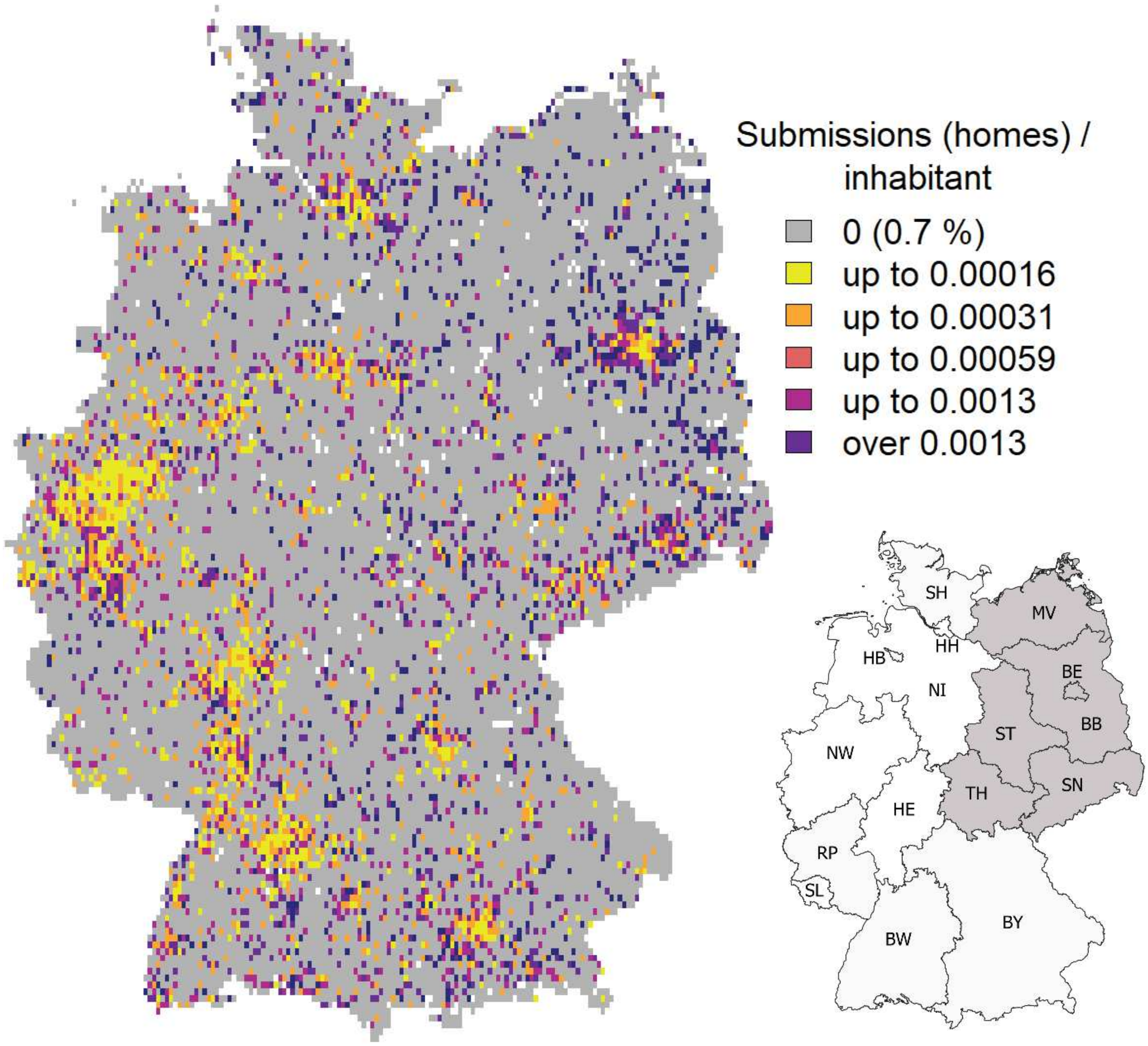
Supplementary Table S1: Covariates (i) automatically exported by the CULBASE database and (ii) manually created for this study (these are highlighted in grey).

Variables	Explanation
Identification (Id)	Identification number
Species code (specc)	Internal hierarchical key for species, numeric
Species name original (spec.o)	Species or - in not determinable cases - genus name, character
Species name adapted (specn)	Species names only, genus set to NA, character
Geo-reference (xvalue)	Geographical latitude, decimal in WSG1984
Geo-reference (yvalue)	Geographical longitude, decimal in WSG1984
Village name (villn)	Nearest village of catch location, character
Corine Landcover Category code (coverc)	Corine Land Cover Category (level 3), numeric
Corine Landcover Category name (covern)	Corine Land Cover Category (level 3), character
County name (countyn)	Federal state name in English, character
County code (countyc)	Federal state by numbers 1 to 16, numeric
Municipality name (munin)	Municipality name of nearest village, character
Date (catchdate)	Date of catch, YYYY-MM-DD
Biotope original (bio.o)	Participant notion about find spot, character
Biotope category (biocat)	Participant notion about find spot categorised (agricultural area, artificial vegetated area, captive breeding, cemetery, coastal wetland, farmstead/stable, forest, home indoors, home outdoors, industrial area, inland water, inland wetland, intersection home indoor/outdoor, mineral extraction site, overwintering ground, public building, transport area, transport vehicle, trap), character

Supplementary Figure S1: Raster maps of the non-factor predictors considered (5 x 5 km^2 grid across Germany).



Supplementary Figure S2: Raster grid of Germany (5 x 5 km^2 cell size) showing per-capita rates of submissions from biotope category 'home' (white grid cells = zero submission and zero/invalid population data). Federal states of Germany (SH = Schleswig-Holstein, HH = Hamburg, HB = Bremen, NI = Lower Saxony, NW = North Rhine-Westphalia, HE = Hesse, RP = Rhineland Palatinate, SL = Saarland, BW = Baden-Wuerttemberg, BY = Bavaria, MV = Mecklenburg Western-Pomerania, BB = Brandenburg, BE = Berlin, ST = Saxony-Anhalt, SN = Saxony, TH = Thuringia. Raster map was created in R version 3.5.2., the German map outlining the federal states was drawn using QGis version 3.4.2. (Quantum GIS Geographic Information System, Open Source Geospatial Foundation Project. http://www.qgis.org/en/site/).



Chapter 4 | Buzzing homes: Using citizen science data to explore effects of urbanisation on indoor mosquito communities

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insects

Article

Buzzing Homes: Using Citizen Science Data to Explore the Effects of Urbanization on Indoor Mosquito Communities

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Simple Summary: Many mosquito species can transmit pathogens and may pose a risk to human health. With increasing urbanization and alteration of natural habitats, the composition of mosquito communities is changing, with some species thriving particularly well in and adjacent to human settlements. In the present study, indoor mosquito collections submitted to the citizen science project 'Mückenatlas' were used to investigate the composition, abundance, and diversity of species of different urbanization levels, and to detect preferences for less or more urbanized areas. We found that species richness and diversity decreases with increasing urbanization, and some important vector species are captured most frequently in densely urbanized regions. Our results highlight the importance of long-term mosquito monitoring to learn how these vectors respond to habitat change caused by humans. Only with sufficient knowledge about the ecology of mosquitoes can we assess risks, plan counter strategies, and take action.

Abstract: Urbanization has been associated with a loss of overall biodiversity and a simultaneous increase in the abundance of a few species that thrive in urban habitats, such as highly adaptable mosquito vectors. To better understand how mosquito communities differ between levels of urbanization, we analyzed mosquito samples from inside private homes submitted to the citizen science project 'Mückenatlas'. Applying two urbanization indicators based on soil sealing and human population density, we compared species composition and diversity at, and preferences towards, different urbanization levels. Species composition between groups of lowest and highest levels of urbanization differed significantly, which was presumably caused by reduced species richness and the dominance of synanthropic mosquito species in urban areas. The genus *Anopheles* was frequently submitted from areas with a low degree of urbanization, *Aedes* with a moderate degree, and *Culex* and *Culiseta* with a high degree of urbanization. Making use of citizen science data, this first study of indoor mosquito diversity in Germany demonstrated a simplification of communities with increasing urbanization. The dominance of vector-competent species in urban areas poses a potential risk of epidemics of mosquito-borne diseases that can only be contained by a permanent monitoring of mosquitoes and by acquiring a deeper knowledge about how anthropogenic activities affect vector ecology.

Keywords: biodiversity; citizen science; epidemiology; mosquitoes; urbanization

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1. Introduction

With continuing outbreaks of mosquito-borne diseases in Mediterranean countries and recent cases of West Nile fever as far north as Germany, the management of mosquito vector species has become an important political and scientific issue throughout Europe [1]. Many countries have implemented mosquito-monitoring programs based on various methodological approaches. The collected data are used to update and predict species distributions, such as tracking the spread of invasive or native mosquito species that are capable of transmitting disease agents such as dengue, chikungunya, West Nile, or Zika viruses [2,3].

Urbanization is thought to be one of the main anthropogenic drivers of changes in mosquito species composition and relative abundance through loss of natural larval habitats and the creation of new artificial ones [4–6]. With urbanization, an increase in population densities of those mosquito species is expected because they thrive in urban environments and in the vicinity of humans due to a selective advantage, e.g., the capability of breeding in artificial containers or the preference for human blood hosts. These include species of the genera *Aedes*, *Anopheles*, and *Culex*, some of which have invasive potential and can transmit a variety of pathogens, such as the Asian tiger mosquito *Aedes albopictus* [7]. Invasive species are highly adaptable and often prosper in urban environments, amplifying the risk of mosquito-borne disease outbreaks [8]. Consequently, it is of utmost interest and importance for risk assessment and epidemiological modelling to know which mosquito species dwell in human settlements and how mosquito communities differ based on surrounding environmental features such as the level and structure of urbanization.

Few studies about mosquito diversity in urban regions of Europe exist, with only two pertaining to metropolitan areas in Germany [9,10] and only a handful for other European countries [11–16]. By comparison, responses of mosquito communities to urbanization have been investigated more intensively in North and South America [17,18], Asia [19,20], Australia [21], and Africa [22], probably due to past or recent outbreaks of mosquito-borne diseases. The majority of these investigations focus on identifying hotspots of one or two synanthropic, highly vector-competent species such as the yellow fever mosquito *Aedes aegypti* or *Ae. albopictus* in relation to urbanization [12,23]. Studies have rarely been aimed at capturing the entire mosquito biodiversity and relating it to urbanization [17]. A key reason for this lack of studies is that access to private properties is limited. The alternative—placing traps on public land—is risky and too often results in damaged or stolen devices [24]. As a result, it is deemed necessary to include residents in the research process via a citizen science approach in order to safely collect data from around and inside homes.

Citizen science has become an increasingly common form of research over the last decade [25–27]. Among its many benefits for society, it facilitates data collection on a spatial and temporal scale that scientists alone are barely able to cover [28]. However, there are doubts about the explanatory power of data gathered by non-professionals, as they tend to contain observation biases such as uneven spatial coverage [29–31], inconsistent sampling behavior [32,33], or uncertainties in object identification by the participants [34]. On the other hand, advanced methods have been developed in recent years for each stage of the scientific process, including avoidance of bias through adapted protocols [35,36], verification of data using artificial intelligence [34,37,38], detection and statistical compensation of biases [33,39–42], and data integration [43].

Regarding urban ecology, data collected by citizens have been used in many studies, such as investigating the biodiversity of taxa like birds [44] or phorid flies [45], tracking invasive species [46], or initiating conservation action [47]. Many citizen science projects are aimed at monitoring and controlling mosquitoes as they are easily identifiable and people are personally concerned due to health implications or nuisance. In Italy, for example, a novel approach by Caputo et al. [48] used citizen surveys via an app (ZanzaMapp) to estimate mosquito abundance and nuisance. By means of the originally Spanish 'Mosquito Alert' smartphone app, participants could upload pictures of five important mosquito vectors and corresponding breeding habitats to inform health authorities in the Barcelona region [49]—a successful concept that has been launched in 17 other countries in 2020. Despite the relevance for public health, there is, to our knowledge, no study that explicitly focuses on the indoor biodiversity of mosquitoes. Indeed, very few studies have been conducted that target the insides of the participants' residences, although investigating the ecology and evolution of the indoor biome is an emerging research field and is predestined for citizen science approaches [50].

The lack of knowledge about which mosquitoes actually enter human residences might be partly filled by data from the citizen science project 'Mückenatlas', an implemented part of the German mosquito monitoring program. To gain knowledge about the occurrence and distribution of native and invasive mosquito species, this program was initiated in 2011 and consists of several monitoring schemes such as collecting eggs by ovitrapping, larvae by dipping, and adults by placing attractant traps. This systematic approach was extended by the passive surveillance instrument 'Mückenatlas' in 2012, where people were asked to collect and submit mosquito samples without any protocol and training [51]. By 2020, approximately 154,000, mostly hand-caught, mosquitoes had been submitted as physical samples, with more than 66% coming from the inside of the participants' homes, thus providing a rich data source for the current study.

This study investigates the indoor diversity of mosquitoes based on 'Mückenatlas' submissions from inside private homes. We take a multi-level approach to determine and specify differences of mosquito communities from varying levels of urbanization, defined by two indicator variables, *soil sealing* (surface imperviousness) and *human population density*. First, we visualize and test whether mosquito communities differ among levels of urbanization. Second, rarefied species richness and effective Shannon diversity as biodiversity indices are calculated to find explanations for the found differences. Finally, we investigate whether mosquitoes, aggregated into genera, show preferences for certain levels of urbanization. In the broader context of the uniqueness of the dataset, we simultaneously investigate whether the information contained in the data confirms our knowledge of mosquito ecology or even leads to new insights.

2. Materials and Methods

2.1. The Citizen Science Dataset

The 'Mückenatlas' project calls upon the German population to catch mosquitoes, kill them without damage, e.g., by freezing, and send them together with a submission form that is downloadable from the project website (www.mueckenatlas.com) to the involved institutes. Every participant is rewarded with a personal email or letter with details about the catch and, if desired, an individual marking on the collectors' map on the project website. The institutes will morphologically and, if necessary (i.e., in ambiguous cases), genetically identify the submitted sample to species level using the identification keys of Becker et al. [52] and Schaffner et al. [53] and CO1 barcoding [54], respectively. We considered mosquito groups or complexes (e.g., *Anopheles maculipennis* complex, *Culex pipiens* complex, *Aedes annulipes* group) as single taxa to account for impossibilities or uncertainties in differentiating females between species. These complexes or groups are referred to as *species* for simplification (Supplementary Materials Table S1). All data corresponding to a mosquito submission is uploaded to the German mosquito database CULBASE.

Data were extracted from CULBASE for the years 2012 to 2019. The dataset consisted of 26,060 entries, with each entry representing one mosquito species submission from one location on a unique date, hereafter referred to as submission. One submission might contain several individuals of the same species when participants caught more than one mosquito on the same occasion; these are then summed up in an additional count variable. The exported dataset comes with an automatically generated suite of covariates, such as geo-coordinates, land-use type, and collection date. In addition, the dataset has a variable that reflects the participants' comments on the collection location, such as garden, house, or stable etc. These were categorized manually, and all entries were then filtered according to the locations of the submissions from the interior, resulting in 16,933 observations.

2.2. Classification of Urbanization Level by Indicator Variables

To define the corresponding level of urbanization of every observation, we used two indicator variables: (1) percentage of sealed soil (imperviousness) and (2) population density as the number of individuals per square kilometer. Concerning sealing, we basically followed the categorization by Böcker [55] and defined a value from 0 to 50% as low, from 51 to 70% as moderate, from 71 to 90% as strong, and from 91 to 100% as very strong. A grid of the percentage of *soil sealing* related to the surface of Germany with a resolution of one square kilometer served as the data base [56], from which the corresponding value was extracted for each individual submission location and then allocated to either low, moderate, strong, or very strong sealing. In addition to *soil sealing* as a common measure for urbanization, *human population density* was considered because humans unknowingly create numerous larval habitats, e.g., in private gardens, green spaces, or cemeteries, while also providing reliable sources of blood meals, either by themselves or by their pets and their livestock. The assessment according to *human population density* was derived from the degree of urbanization classification (DEGURBA) of the EU [57], categorizing a population density of up to 300 inhabitants per square kilometer as rural, between 300 and 5000 inhabitants per square kilometer as peri-urban, and above 5000 inhabitants per square kilometre as urban. We created a human population raster with square kilometer grid cells based on data from the German census in 2011 [58], extracted the corresponding data for every submission-related collection site, and assigned categories of either rural, peri-urban, or urban (see Supplementary Materials, Figure S1, for maps on distribution of both indicator variables across Germany). For simplification, we further refer to mosquito communities by level of urbanization as groups. Data preparation and creation of spatial covariates were conducted in R version 3.6.3 [59] with packages dplyr [60], raster [61], and rgdal [62].

2.3. Statistical Analysis

We used non-metric multidimensional scaling (NMDS) to explore differences in mosquito community composition according to level of urbanization, a common approach to visualize multidimensional data in two-dimensional space. This ordination technique is based on ranked proximities between the subjects of interests, in this case, the abundance (submission numbers) of mosquito species and level of urbanization. Each year of data collection (2012 to 2019) was treated as a replicated sample, and the respective urbanization levels of both indicators represented the sampling units. The impact of frequently submitted species was minimized by Wisconsin double standardization and square-root transformation, and the Bray-Curtis index was used to create dissimilarity matrices based on the species submission numbers within each group. For both runs with command *metaMDS* (*vegan* package), we calculated the stress level, which is an indicator of the reliability of the result, e.g., an ordination with a stress greater than 0.3 could also have occurred arbitrarily. To test the groups for statistically significant differences in species communities, a permutational multivariate analysis of variance (PERMANOVA) was applied, followed by a pairwise comparison of groups with a permutation test based on t-statistics (homogeneity of dispersion, PERMDISP).

We chose two biological diversity metrics, rarefied species richness, and effective Shannon diversity, which are robust against varying sample sizes and abundances, and facilitate comparing differences in biodiversity between groups. Rarefaction is a standardization technique that suits the ‘Mückenatlas’ data as it accounts for the different sample sizes and allows a fair comparison between the urbanization categories. For all calculations, we used the smallest sample size for each urbanization level in each year as the number of sub-samples randomly drawn from the larger samples to estimate expected species richness (sample-based rarefaction [63] with command *rarefy* of the vegan package).

The original Shannon–Wiener index was not used, as it is difficult to interpret and not robust against differences in abundances; in our case, number of submissions and sample sizes. These disadvantages are partially resolved by using the exponential of the

Shannon–Wiener index to convert it to effective Shannon diversity. It indicates the effective number of species, i.e., those that are equally common, and allows us to directly compare the results among groups [64]. Following the calculation of rarefied species richness and effective Shannon diversity, we applied ANOVA for group-wise and post-hoc Student's t-test with the Bonferroni–Holm adjustment for pairwise comparisons.

To find out whether the citizen science data can be used to infer preferences of mosquito genera for a certain level of urbanization, a Chi-square test of homogeneity was applied. Because the number of submissions from the considered level of urbanization varied greatly, we adapted the method of Bates et al. [65] by using weighted expected counts in the Chi-square test, i.e., we calculated for each of the five genera the summed ratio of the other four genera's observations from the different levels of urbanization to approximate the corresponding sampling effort in the expected count for the target genus. To test the single genera for significant tendencies of being submitted from certain levels of urbanization, the Chi-square residuals were computed and positive and negative tendencies visualized. These analyses were performed with R packages dplyr [60], vegan [66], ggpubr [67], and ggplot2 [68].

We opted for statistical analyses that allowed us to investigate how mosquito communities change along an urbanization gradient. For this purpose, we used species abundances for NMDS and biodiversity indices as well as abundances of genera for the Chi-square tests. A more detailed ecological examination of the occurrences of individual species, their habitat preferences, and contributions to differences in mosquito communities are beyond the scope of the current study and will be carried out in the future.

3. Results

Distribution of submissions over years and urbanization levels varied greatly (Figure 1 and Supplementary Materials, Table S2). Most submissions were recorded in 2016 and 2017, a phenomenon based on media topicality and recorder bias that has already been investigated in previous studies [30,69]. In general, a higher number of submissions came from lower to medium levels of urbanization than from very densely populated areas. The uneven distribution across the groups according to population density (inhabitants per square km) is striking, with over two thirds of the entries coming from grid cells with 300 to 5000 inhabitants, which is not representative of the latest share of DEGURBA classes in Germany (34% rural, 42% peri-urban, 24% urban [57]).

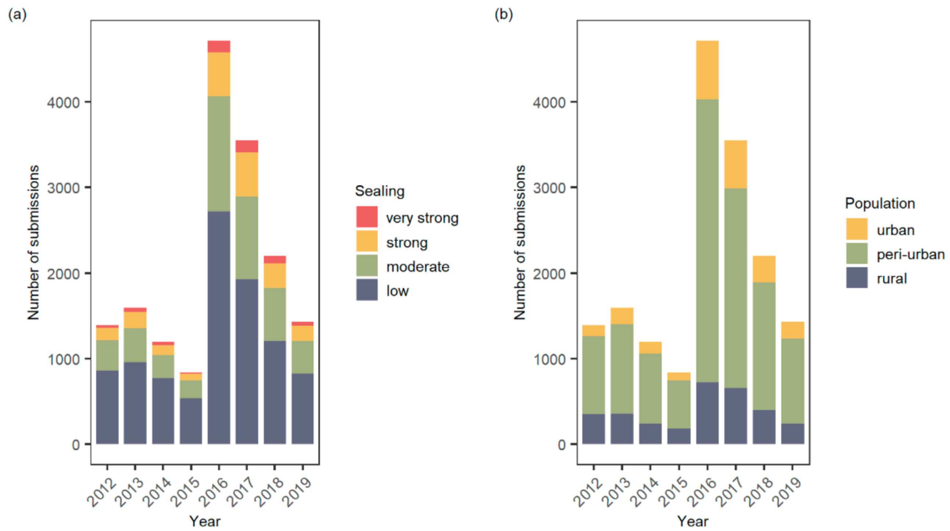

Figure 1. Numbers of submissions by year and level of urbanization, the latter assessed by (**a**) *soil sealing* and (**b**) *human population density*.

The NMDS plots show differences in yearly mosquito assemblages by groups for both indicators of soil sealing (stress value = 0.14, R^2 = 0.98) and human population density (stress value = 0.14, R^2 = 0.98). Stress values indicate a fairly good fit (Figure 2). Visually, the NMDS plots (Figure 2) suggest that mosquito communities of high and low urbanized areas are distinct. The PERMANOVA is significant, and the variance explained is fair for both indicator variables of soil sealing (R^2 = 0.55, $p < 0.001$) and human population density (R^2 = 0.44, $p < 0.001$) (Supplementary Materials, Table S3, *p*-values based on permutations).

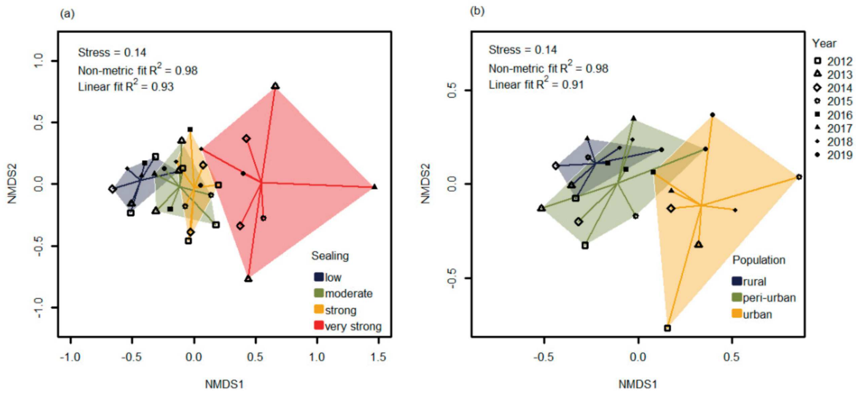

Figure 2. Non-metric multidimensional scaling (NMDS) showing differences in mosquito species communities of different levels of urbanization assessed by (**a**) *soil sealing* and (**b**) *human population density*, using years as replicates (symbols).

This result might indicate that there are different species present (or present in different abundances), depending on urbanization level. Significant PERMDISP for indicator *soil sealing* suggests that, for this variable, the difference might rather be due to within-group dispersion, e.g., of greater abundance variation in the group of low sealing than in the groups of strong and very strong sealing. The case was different for the indicator *human population density*, where the PERMDISP test was not significant. To better understand these patterns, biodiversity indices were calculated.

To explore the characteristics of the data, we plotted species richness, rarefied species richness, adjusted species richness, the Shannon–Wiener index, effective Shannon diversity, and the adjusted Shannon–Wiener index by year (Supplementary Materials, Figure S2). We then computed and visualized rarefied species richness and effective Shannon diversity per urbanization group and indicator (Figure 3). According to the ANOVA, rarefied species richness is not significantly different among groups for both indicator variables, i.e., the level of urbanization does not appear to have any influence on the number of species submitted when accounting for different sample sizes. With respect to effective Shannon diversity, we found significant differences between low and strong levels of urbanization. With a higher level of urbanization, the number of effective species decreases, i.e., there is a strong dominance of a few species (*Cx. pipiens* complex, *Culiseta annulata* and *Aedes japonicus*) in urban areas (Figure 3).

The omnibus Chi-square test revealed significant differences in the number of genera submitted per group for both indicators, *soil sealing* (χ^2 = 80.5, $p < 0.001$) and *human population density* (χ^2 = 159.91, $p < 0.001$). A follow-up with single comparisons (row-wise by genera to find out tendencies for level of urbanization) showed significant differences in submission numbers for most genera, except for *Culiseta*, regarding the urbanization indicator *soil sealing*, and *Coquillettidia*, regarding the indicator *human population density* (Table 1).

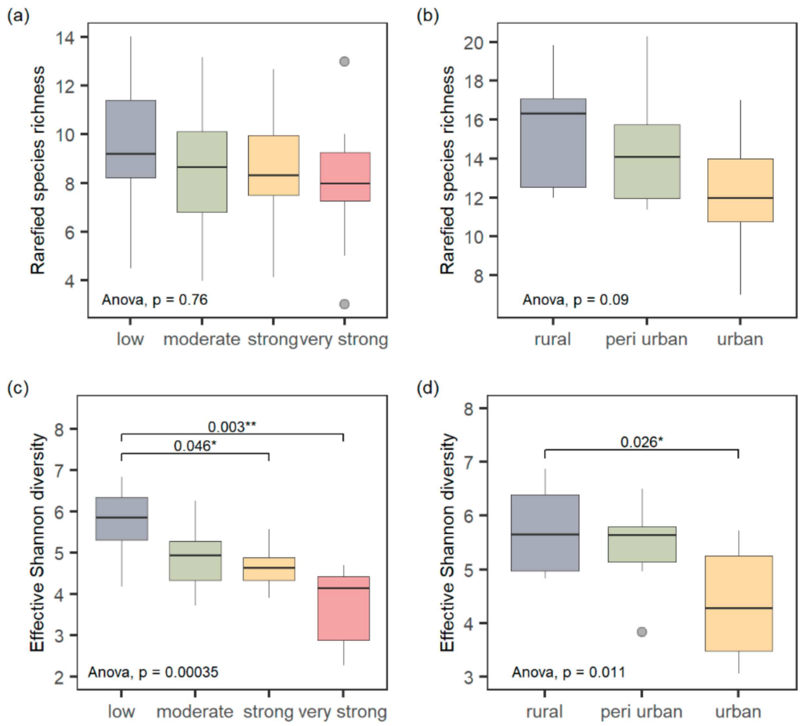

Figure 3. Boxplots comparing rarefied species richness, (**a**,**b**), and effective Shannon diversity (number of equally common species), (**c**,**d**), by urbanization level based on two indicators, *soil sealing* and *human population density*, using years as replicates. Thick black lines denote medians, first and third quartiles are shown by lower and upper hinges, and whiskers represent distance from hinge to the farthest value within the 1.5 interquartile range. Outliers are displayed individually. Symbols * and ** indicate statistical significance at $\alpha < 0.05$ and < 0.01 based on t-tests with the Bonferroni–Holm correction (adjusted *p*-values displayed).

Table 1. Chi-square test of homogeneity for the number of observations per urbanization indicator—*soil sealing* and *human population density*—of five mosquito genera. Expected counts are weighted by the proportion of samples of the four other genera (ns = not significant).

Genus	Observed Counts				Weighted Expected Counts				χ^2	*p*-Value
Sealing	**Low**	**Moderate**	**Strong**	**Very Strong**	**Low**	**Moderate**	**Strong**	**Very Strong**		
Aedes	2386	1064	427	86	2268	1063	489	143	36.61	<0.001
Anopheles	464	149	65	12	397	187	83	23	28.23	<0.001
Coquillettidia	238	79	31	12	208	97	43	12	11.21	<0.011
Culex	4424	2150	1023	300	4706	2092	877	222	70.40	<0.001
Culiseta	2297	1102	480	144	2341	1073	482	128	3.70	ns
Population	**Rural**	**Peri-Urban**	**Urban**		**Rural**	**Peri-Urban**	**Urban**			
Aedes	645	2830	488		738	2683	543		4.18	<0.001
Anopheles	233	413	44		128	467	94		131.24	<0.001
Coquillettidia	80	239	41		67	244	49		41.81	ns
Culex	1462	5311	1124		1470	5346	1081		71.62	<0.028
Culiseta	732	2670	621		749	2723	551		8.51	<0.001

By visualizing the Pearson residuals of the Chi-square test to explore tendencies of mosquito genera for a certain urbanization level (Figure 4), a general preference of the genus *Anopheles* for rural areas, of the genera *Culex* and *Culiseta* for more densely populated environments, and of the genus *Aedes* for peri-urban spaces could be demonstrated.

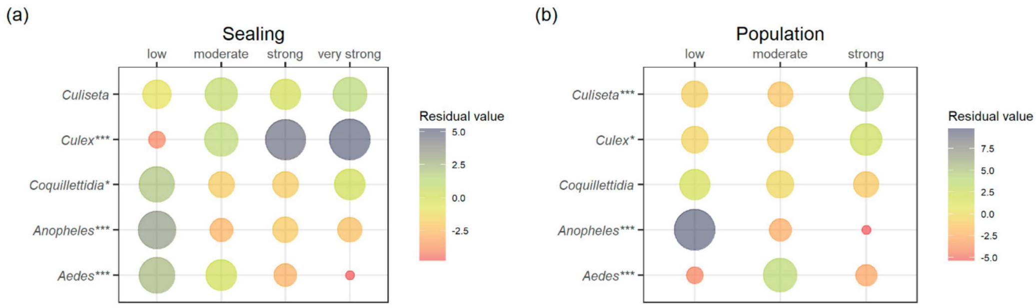

Figure 4. Tendencies of genera for a certain level of urbanization categorized by the indicators *soil sealing* (**a**) and *human population density* (**b**) by means of Pearson residuals. Dot size corresponds to the overall contribution to the total Chi-square value. Positive scores indicate an attraction (green to blue) and negative scores indicate a repulsion between rows and columns (yellow to red). Significant differences from row-wise comparisons are indicated (* = $p < 0.05$, *** = $p < 0.001$).

4. Discussion

This is the first large-scale indoor mosquito biodiversity study for Germany, based on 16,933 submissions to the citizen science monitoring scheme 'Mückenatlas' from inside the homes of the participants between 2012 and 2019. Without the contribution of citizens, it would not have been possible to collect such data and analyze the biodiversity of mosquitoes in human housing. Therefore, citizen science seems almost a necessity for indoor biome research, at whatever scale. For example, at the lowest scale, citizens could participate simply by letting scientists into their homes so that professionals can systematically sample there (e.g., [70]). In this case, the involvement of citizens in the scientific process is extremely limited, as is the amount of data that is collected because this is highly dependent on financial and human resources. The scaling of projects can be expanded in time and space the more autonomously and flexibly citizens are involved, e.g., in physical data sampling, photorecording observations, or other parts of the scientific process [71].

However, while the flexibility of the protocol leads to a high number of participants, it also induces data bias [31]. In the case of the 'Mückenatlas' scheme, differences in sample size by urbanization level reflects a spatial bias, predominantly caused by population density, a phenomenon well-known from opportunistic citizen science data [29,30,33,72]. In this study, the huge differences in sample sizes within years and between the groups of urbanization level were counteracted with rather simple methods to demonstrate the general interpretability and usefulness of the opportunistic data collection for addressing ecological questions. Regardless of the biases that need to be addressed with methods according to the analysis objective, involving citizens might be the only way to get indoor biome data at all. Citizen science is also crucial for collecting a meaningful amount of information when it comes to national, continental, or even cross-continental comparative studies.

With the support of citizens providing valuable information from their homes, this study found that indoor mosquito communities differ by urbanization level. A location effect could be identified for the indicator *human population density*, whereas differences of the indicator *soil sealing* might be due to within-group dispersion, e.g., changes in relative abundances within the group over the years. By further applying biodiversity indices to shed more light on these differences, we see that the tendency that rarefied species richness decreases with increasing urbanization, as already demonstrated in smaller scale studies [11,15,73]. The higher species richness of sample aggregations stemming from rural homes appear to reflect a more heterogeneous landscape featuring habitats suitable for rarer and more specialized mosquito species. However, total species richness independent from level of urbanization varies greatly over time (Supplementary Materials, Figure S2), suggesting that fluctuating factors other than *soil sealing* and *human population density* shape the recordable diversity of species. Climatic conditions greatly influence the development and composition of mosquito communities [74–76] and can lead to higher densities, nuisance, and media topicality, thus increasing the probability of a submission by a 'Mückenatlas' participant [30]. In addition, the opportunistic data collection is not only biased by human population and climatic variability but also by taxonomic preferences [32]. In the case of citizen science programs where both native and invasive taxa are of interest, people tend to look out for the intruders [77,78]. Therefore, species richness estimates from citizen science data need to be carefully interpreted and, if possible, combined or cross-checked with professional data [79,80].

Comparison of effective Shannon diversity also indicates that diversity decreases with urbanization, thereby supporting the results of rarefied species richness estimates and partly explaining the significant difference of the groups. Although a meta-study by Fenoglio et al. [81] found hematophagues to be the only group of arthropods that generally seems to positively respond to urban environments, mosquito communities are less diverse in populated and sealed areas [11,73,82]. While the disturbance of natural habitats through deforestation or drainage of wetlands negatively affects the life cycle of rather specialized species, adaptive generalists are promoted by urbanization. Indeed, some of the most competent vectors of the *Aedes*, *Culex*, and *Anopheles* genera show tendencies to exploit edges of disturbance such as forest-arable land transitions, abandoned stables, or construction sites at urban expansion borders [21,83]. The tendency of submitted *Aedes* specimens to be collected predominantly in peri-urban areas could therefore also be due to high submission numbers of *Ae. japonicus*, a species that also prefers these transition zones, to the 'Mückenatlas' scheme [84].

Of all mosquito genera, *Culex* is the most frequent in urban and strongly sealed areas, mainly due to the high numbers of *Cx. pipiens* complex submissions. Members of the *Cx. pipiens* complex are ecologically and physiologically flexible and are known to thrive in urban areas [85,86]. They reproduce as easily as other urban-adapted mosquito species in widely available artificial containers [87]. As such, artificial containers offer microhabitats that enable mosquito species to survive despite dry seasons or droughts [88]. Even the emergence of the human-biting preference of *Ae. aegypti* or a shift of breeding site selection by the minor malaria vector, *Anopheles plumbeus*, towards man-made habitats can now be attributed to adaptation to urban regions with reliable water sources [88–90].

5. Conclusions

Our results demonstrate that citizen science is an appropriate method in the process of analyzing the indoor biome and, moreover, that the 'Mückenatlas' opportunistic data collection not only confirms existing knowledge but also enables completely new insights into urban mosquito ecology. Although the analysis is greatly simplified by combining all submissions and creating artificial groups of mosquito communities, regardless of the geographical or climatic conditions of the original location, the explanatory power of the data is strong—certainly due to the large observation number. Citizen science is therefore not only recommended for inclusion in formal mosquito monitoring programs to enlarge the data basis for better risk assessments and modelling, it could also unleash a truly invaluable resource that can significantly advance the global indoor biome data—the people at home [91].

The results of this study are also relevant for public health in Germany. The high submission numbers of *Cx. pipiens* complex from within people's homes and from high levels of urbanization (i.e., densely populated areas) highlight the risk of human exposure to mosquito-borne disease in the country. The simplification of mosquito communities in urban areas worldwide, as confirmed by our study, is caused by less differentiation of breeding sites through homogenization of urban habitats, which is in turn linked to higher infection rates [11,73]. Initial natural diversity would not recover, even over a century after being urbanized [17], so the natural mechanism of reducing species-related nuisance through intraspecific competition will not be restored. In the face of accelerated urbanization and global warming, precautions can only be taken with further intensive surveillance and knowledge acquisition. Therefore, continuous mosquito monitoring on large scales, even cross-national, with conventional methods and citizen science are just as essential as targeted small-scale field studies to achieve a better understanding of vector ecology.

Supplementary Materials: The following is available online at https://www.mdpi.com/article/10.3390/insects12050374/s1, Table S1: Species list with corresponding numbers of submissions to the 'Mückenatlas'. Table S2: Total counts of submissions by year and level of urbanization; Table S3: PERMANOVA results based on Bray–Curtis dissimilarities using square-rooted abundance data for indoor mosquito communities grouped by (a) *soil sealing* and (b) *human population density*; Figure S1: Distribution of indicator categories across Germany; Figure S2: Differences in the biodiversity indices with or without consideration of the sampling effort across all years, regardless of urbanization indicator. Figures S1 and S2 were produced in R [59].

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Appendix: Supporting Information Chapter 4

Table S1: Species list with corresponding numbers of submissions to the 'Mückenatlas'.

Species	No. of submissions
Ae. aegypti	1
Ae. albopictus	54
Ae. annulipes group	337
Ae. caspius	73
Ae. cataphylla	63
Ae. cinereus/geminus/rossicus group	40
Ae. communis	13
Ae. detritus	13
Ae. dorsalis	1
Ae. flavescens	6
Ae. geniculatus	980
Ae. intrudens	2
Ae. japonicus	858
Ae. koreicus	1
Ae. leucomelas	22
Ae. pullatus	4
Ae. punctor	15
Ae. refiki	1
Ae. rusticus	73
Ae. sticticus	433
Ae. vexans	973
An. claviger complex	45
An. maculipennis complex	396
An. petragnani	1
An. plumbeus	248
Cq. richiardii	360
Cs. alaskaensis	1
Cs. annulata/subochrea	3933
Cs. glaphyroptera	7
Cs. longiareolata	6
Cs. morsitans/fumipennis	76
Cx. hortensis	22
Cx. modestus	16
Cx. pipiens complex	7837
Cx. territans	22

Table S2: Total counts of submissions by year and level of urbanisation.

	Urbanisation by sealing				Urbanisation by population			
	low	moderate	strong	very strong	rural	peri-urban	urban	**total**
2012	863	353	143	33	350	916	126	1392
2013	959	397	193	49	358	1043	197	1598
2014	773	268	118	37	240	819	137	1196
2015	535	213	80	12	180	567	93	840
2016	2720	1348	507	143	723	3307	688	4718
2017	1928	967	514	143	659	2332	561	3552
2018	1207	618	290	87	400	1488	314	2202
2019	824	380	181	50	242	991	202	1435
total	9809	4544	2026	554	3152	11463	2318	**16933**

Table S3: PERMANOVA results based on Bray-Curtis dissimilarities using square-rooted abundance data for indoor mosquito communities grouped by a) soil sealing and b) human population density.

PERMANOVA

Urbanisation indicator		**Df**	**SumofSq**	**Pseudo-F**	**R^2**	**p-value**
Sealing						
	Groups	3	1.9766	11.29	0.5474	0.001***
	Residuals	28	1.6340		0.4526	
	Total	31	3.6106		1.0000	
Population						
	Groups	2	0.7582	8.248	0.4399	0.001***
	Residuals	21	0.9651		0.5601	
	Total	23	1.7233		1.0000	

PERMDISP

Urbanisation indicator		**Df**	**SumofSq**	**Mean Sq**	**Pseudo-F**	**p-value**
Sealing						
	Groups	3	0.0411	0.0136	2.9615	0.041*†
	Residuals	28	0.1294	0.0046		
Population						
	Groups	2	0.0117	0.0059	1.9526	0.159
	Residuals	21	0.0631	0.0030		

Df: Degrees of freedom; SumofSq: sum of squares; Pseudo-F: F-value based on 999 permutations; p-valu: based on 999 permutations (lowest P-value possible: 0.001), †significant differences in permutated p-values for the soil sealing category pairs ‘low’-‘very strong’ and ‘moderate’-‘very strong’.

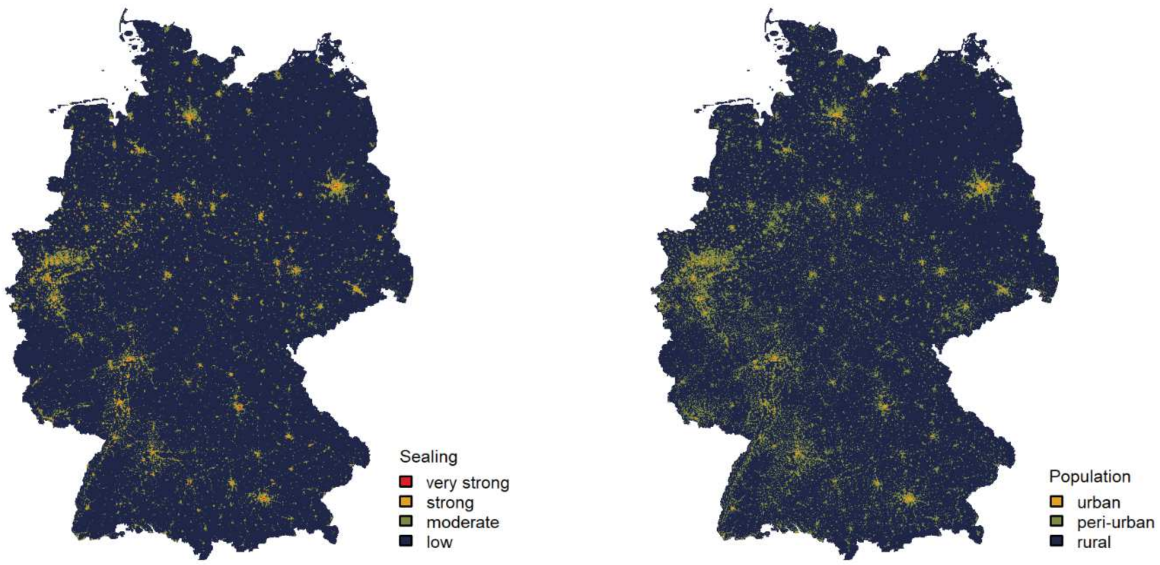

Figure S1: Distribution of indicator categories across Germany. Raster grid with cell size of one square kilometre for soil sealing (left) and human population density (right).

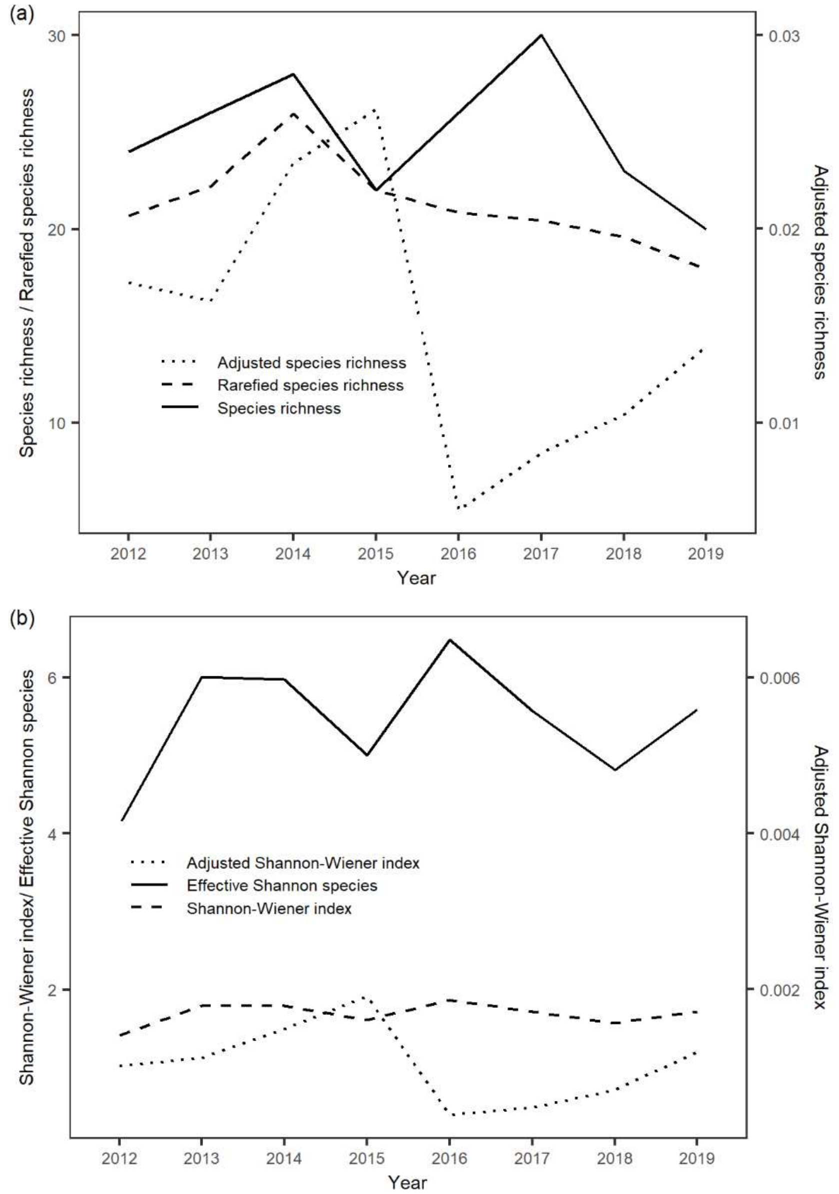

Figure S2: Differences in the biodiversity indices with or without consideration of the sampling effort across all years, regardless of urbanisation indicator. (a) Species richness, rarefied species richness (based on the smallest sample size of 840 submissions in 2015) and adjusted species richness (species richness divided by the respective number of submissions per year) (b) Shannon-Wiener-Index, effective Shannon diversity and adjusted Shannon-Wiener index (Shannon-Wiener index divided by the respective number of submissions per year). Figure calculation and design based on [92, see reference number in main article].

Chapter 5 | How media presence triggers participation in citizen science – the case of the mosquito monitoring project 'Mückenatlas'

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How media presence triggers participation in citizen science – the case of the mosquito monitoring project 'Mückenatlas'

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Abstract

Since 2012, the citizen science project ‘Mückenatlas’ has been supplementing the German mosquito monitoring programme with over 28,000 submissions of physical insect samples. As the factors triggering people to catch mosquitoes for science are still unknown, we analysed the influence of mass media reports on mosquito submission numbers. Based on a theoretical framework of how mass media affect citizen responsiveness, we identified five possible influencing factors related to citizen science: (i) project awareness, (ii) attention (economy), (iii) individual characteristics of citizen scientists and targeted communication, (iv) spatial differences and varying affectedness, and (v) media landscape. Assumptions based on these influencing factors were quantitatively and qualitatively tested with two datasets: clipping data of mass media reports (online, television, radio, and print) referring to or focussing on the ‘Mückenatlas’, and corresponding data of ’Mückenatlas’ submissions between 2014 and 2017. In general, the number of media reports positively affected the number of mosquito submissions on a temporal and spatial scale, i.e. many media reports provoke many mosquito submissions. We found that an already heightened public and media awareness of mosquito-relevant topics combined with a direct call-to-action in a media report title led to a maximum participation. Differences on federal state level, however, suggest that factors additional to quantitative media coverage trigger participation in the ‘Mückenatlas’, in particular the mosquito affectedness of the resident population. Lastly, media types appear to differ in their effects on the number of submissions. Our results show under which circumstances the media presence of the 'Mückenatlas' is most effective in activating people to submit mosquito samples, and thus provide advice for designing communication strategies for citizen science projects.

Keywords: Biodiversity monitoring, Citizen Science, Cross-correlation, Media relations, Mosquitoes, Point pattern analysis, Public participation

1. Introduction

With continuing outbreaks of mosquito-borne diseases in Mediterranean countries [1] as well as recent cases of West Nile fever as far north as Germany [2, 3], management of vector-competent mosquitoes has become an important political and scientific issue throughout Europe. In 2011, mosquito research returned to the scientific agenda in Germany in the form of a nationwide monitoring programme, aiming at gaining knowledge about the occurrence and distribution of native and non-native mosquito species [4]. Implemented in this programme is the citizen science project 'Mückenatlas' (German for 'mosquito atlas'), one of the longest running and most successful citizen science projects in Germany [5].

The 'Mückenatlas' is hosted at two institutions, the Leibniz Centre for Agricultural Landscape Research (ZALF) and the Friedrich-Loeffler-Institut (FLI), with up to four people working on the sample identification, reference collection, participant support, and database maintenance (S1 Fig). Within the project, citizens are asked to catch mosquitoes (wherever and whenever they want to), to kill them by freezing, to fill out a form downloadable from the project's website (www.mueckenatlas.com) or available at the project's administrative office (S1 File), and submit both the mosquito(es) and the form to the involved research institutions. There, the mosquito sample is determined to species level and the achieved information entered into the German mosquito database, CULBASE. The participants receive an individual letter or email with feedback about the catch and, optionally, a marker with their name or a pseudonym on the collectors' map of the website. In return, the website is regularly updated with research results achieved on the basis of the submissions. After eight years of operation, the 'Mückenatlas' has received more than 28,000 submissions, accumulating to close to 154,000 submitted specimens by June 2021.

The 'Mückenatlas' was launched in 2012 at a time when citizen science – the involvement of the public in scientific research – globally gained momentum. Although public participation in biodiversity monitoring has a long tradition [6-8], it is barely a decade ago when citizen science has become widespread in the scientific community [9-11] and evolved from a mere method to a research subject itself [12-14]. An important reason for the rise of citizen science are web-enabled sophisticated electronic devices, such as smartphones, which facilitate participation in research projects by collecting or processing data [15]. Since 2010, funding programmes have been launched worldwide, citizen science hubs formed, and cooperations across national borders established [16], for example through continental citizen science associations (e.g. the European Citizen Science Association, ECSA) or the founding of the only subject-specific journal to date [17]. At the same time, the scientific discourse about advantages and drawbacks of this emerging scientific discipline is in full swing [18-23].

Due to their familiarity through direct interaction with humans (e.g. biting, buzzing) and their potential health risk through the transmission of pathogens, mosquitoes are highly appropriate subjects for citizen science. Indeed, mosquito-related projects are finished, running or emerging across the globe [24-27]. Yet, in contrast to the 'Mückenatlas', the majority of projects are limited to invasive mosquitoes [28, 29] and are designed for a short period of time [30, 31]. Some projects make use of a smartphone app, such as the originally Spanish 'Mosquito Alert' [32], which was launched in several European countries in 2020, or the Italian 'ZanzaMapp' for measuring mosquito nuisance [33]. Others apply professional traps operated by volunteers [28, 34] or work with physical samples like the ‘Mückenatlas’ [35].

While knowledge about mosquito phenology and distribution in Germany has vastly increased due to the citizens’ involvement [4, 36], the reasons why people participate are still subject to speculation. Only few studies have been conducted on the individuals’ initial motivation to start participating in a citizen science project (but see [37] for online citizen science projects). According to the literature on environmental volunteers, the decision for participation is influenced by the motivation to take part, the personal background that must fit to the project, and the basic condition that the project is known to the potential participant [38, 39].

With regard to the latter, social and traditional media play a key role for both initial and sustaining participation in citizen science [40], but only limited studies exist that connect media coverage with participation rates [41-44]. The media particularly trigger initial participation, by drawing attention to the project either through a timely limited campaign in a concerted approach of traditional and social media channels or through continuous reporting through mass media [41, 44, 45]. Consistent and continuous reporting presents the project’s scientists as trustworthy and accessible experts to the public [42, 44], which, in turn, results in further enquiries from the press.

Active contacts to the media have been established since the beginning of the 'Mückenatlas', especially with the *Deutsche Presseagentur* (German Press Agency, the largest news agency in Germany, in the following abbreviated as 'dpa') as a content provider that triggers print and online media reports. Hecker et al. [46] already speculated that the media is one of four main drivers for effective communication with citizens and a crucial factor for the success of the 'Mückenatlas' in terms of attracting attention and spreading news about the project. Despite this potential relevance, the role of the media or the connection between media coverage and the activation of citizens to participate in the project, respectively, has not been studied so far. Knowledge about this interrelation could help future projects to design more targeted media communication to attract potential citizen scientists.

2. Studying how participation in citizen science projects relates to media presence – a theoretical framework

Communication via traditional mass media is a frequently used approach to attract participants and draw attention to the project [43, 44], but little is known about the effective design of this communication process. Communication theories assume that the effect of a mass communication event on the parts of the recipients depend on numerous influencing factors [47]. Based on a literature review on factors triggering citizen's participation and on impact determinants of communication in mass media, we identified a set of potential influencing factors for the responsiveness/resonance to mass communication events in citizen science projects: (i) project awareness, (ii) attention (economy), (iii) individual characteristics of citizen scientists and targeted communication, (iv) spatial differences and affectedness, and (v) media landscape.

i. Project awareness: Mass media raise awareness, communicate knowledge and can play a mediating role between citizen engagement and attention to socially relevant issues (e.g. [48]. Thus, public awareness and knowledge about a citizen science project certainly is a fundamental precondition to convince citizen scientists to participate [38, 39]. It may thus be assumed that the level of awareness of a project influences the participation/response rate of citizen scientists [44]. As a consequence, we hypothesize that a higher number of media reports leads to a higher participation/response rate, and in the case of the 'Mückenatlas' to a higher number of mosquito submissions on a temporal and spatial scale.

ii. Attention (economy): The capacities of media recipients to receive and process information are limited [49]. Similarly, transmission times and space for texts in print media are finite. Thus, communication actions of citizen science projects always compete for attention with other events of public interest. Regional elections or other emerging incidents can positively or negatively affect the attention given to the project which may result in different citizen's participation rates [44, 50].

iii. Individual characteristics of citizen scientists and targeted communication: There is a number of personal characteristics of citizens that affect the motivation to participate [51-53]. While some of these factors cannot be basically influenced, such as general knowledge, cognitive capacities, curiosity, or the general attitude towards science, others may be stimulated by a targeted communication including emotional language that addresses citizen’s situations and every-day life. Resonance occurs when a topic has meaning for the recipient [54]. This meaning arises for the recipient when he or she can integrate the information received into his or her world of experience. Thus, we assume that (temporal) differences in response rates to media coverage may not only be explained quantitatively, but partly also by qualitative differences in media coverage referring to language style, framing and contextualisation [55].

iv. Spatial differences and varying affectedness: Building on the considerations about individual characteristics of citizen scientists, we assume regional differences in the response rate to media coverage [45]. As different regions have different levels of mosquito occurrence, we assume that in regions with higher levels of affectedness, the response rate is also higher. In addition, there are regional variations in media coverage due to local newspapers and local television and radio stations [56].

v. Media landscape: With regard to the media landscape, there are different types of media (e.g. broadcast, print, online) with different reaches (regional versus national) or target groups (tabloid versus high quality journalism). They therefore filter information about the project and put a message into different contexts, which influences the efficacy of a message in different ways [57, 58]. We assume that different media types may have different effects on the response rate of citizen scientists to the ‘Mückenatlas’ project as indicated by previous studies [41, 43].

The aim of this study is to gain insights on the connection between media coverage and the activation of citizens to participate in citizen science projects. We draw on aggregations of a media monitoring service between 2014 and 2017 to test our assumptions built on the five influencing factors stated above. Based on real data, we explored how effective the ‘Mückenatlas’ mass media approach turned out and thus provide insights for the targeted design of communication strategies for other citizen science projects.

3. Material and Methods

Insect samples were provided voluntarily by citizen scientists after consent was given to the processing of the sender data according to EU General Data Protection Regulation. Further ethical approval was not required because the collected data were anonymised. The use of personal data complies with the EU General Data Protection Regulations.

The study is exploratory and based on data that was not originally collected for the purposes of this study, but to check the effectiveness of the public relations strategy in the context of corporate communications. This is why the dataset has some deficiencies, such as missing distribution data, limited information about the reach or impact area of publishers, or outdated links to online media reports. In addition, the media type ‘print’ is only present in 2017, while the media type ‘online’ is lacking for this year. Nevertheless, the data present a rare opportunity to look for initial clues about the relationship between media coverage and participation.

3.1 Media dataset

The raw data of media reports originated from Argus Data Insights, a media monitoring service that provides information on the media presence of companies, also called media clipping. The company was assigned from 2014 until the end of 2017 by the ZALF to find and consolidate media content for monthly reporting. The service’s engine searched the media types ‘print’, ‘radio’, ‘television’, ‘online’, and ’news agencies’ (dpa) on a national level by using the keywords ‘Mückenatlas’, alone or in combination with ‘Leibniz-Zentrum für Agrarlandschaftsforschung’. Due to the exit of Argus Data Insights from the online business in 2017, the composition of ‘television’, ‘radio’, ‘print’, and ‘online’ varies greatly from year to year, so any temporal evaluation of media types would be meaningless.

The media clipping dataset contained 1072 observations of media reports from 2014 to 2017, with 9 automatically generated covariates, such as date, title, and media type (see S1 Table). To prevent duplication in the descriptive analysis, observations from dpa were not considered, resulting in a total of 934 media reports for quantitative analysis. dpa-releases are editorial contents offered to media, companies, and organisations, i.e. they are not published directly, but are picked up by local, regional, or national media houses which in most cases also take over the entire wording of the original release. dpa-releases containing the 'Mückenatlas' are usually created via the regional studio Berlin-Brandenburg and are then taken over by other dpa-offices (at the national or the federal state level) and offered to the media of their respective impact area.

To approximate the spatial distribution of media reports, we created the variables ‘municipality’ (the smallest administrative division in Germany), ‘xvalue’ and ‘yvalue’ for geo-references, and ‘reach’. For the ‘municipality’ variable, media reports that originated from a certain municipality and targeted a regional audience were assigned the exact municipality name. In all other cases, the media reports were categorised as ‘federal’ or ‘national’ depending on their reach. For those media reports where a specific municipality could be specified, the corresponding geo-coordinates of the community centre were recorded in ‘xvalue’ and ‘yvalue’. For the variable ‘reach’, entries with a geo-reference were assigned to ‘regional’. Media reports that targeted an audience of one or more federal states were categorised as ‘single federal’ or ‘cross federal’, respectively. For entries with national reach, the categories for ‘reach’ were set to ‘national’ (see S2 Table for method description, examples and complete list).

3.2 Mückenatlas’ dataset

Data of mosquito submissions to the ‘Mückenatlas’ were extracted from CULBASE on July 31st, 2018. According to the time period covered by the media clipping dataset, we selected mosquito collections of the years 2014 to 2017 and used the provided geo-references for locating the samples. Each entry of the dataset represents the report of one mosquito species from one location (catching site) independently of specimen counts per sample site, hereafter referred to as ‘submission’. The resulting dataset comprised 16,610 submissions.

3.3 Statistical analysis

Project awareness (i)

To investigate our assumption of a positive correlation between the number of media reports and the number of submissions, we first examined the temporal relationship. The monthly frequencies of both datasets were plotted across all years and tested for a possible time lag between the maxima of media reports and submission numbers using Spearman cross-correlation analysis.

To examine a possible spatial association between number of media reports and number of submissions, we applied a spatial pattern analysis with two spatial point datasets. The first dataset consisted of the geo-locations of 'Mückenatlas' submissions. The second dataset contained those media reports for which we were able to verify a municipality and to which a geo-location could thus be assigned. Consequently, media reports with federal or national reach were excluded from this analysis.

To visually inspect the geographical distribution of media reports and submissions across Germany, we produced density plots, which suggested spatial clustering for both submissions and media reports. To assess the level of clustering of both point pattern datasets, each was individually tested by comparing the geographical distribution of the points to a theoretical point pattern of complete spatial randomness, using the Kolmogorov-Smirnov test. These initial assessments led us to assume that the two point patterns are similarly clustered throughout the country, indicating that locations of clusters of media reports are in the same geographical locations as clusters of submissions.

To investigate this potential relative clustering, the bivariate version of Ripley's K-function (Cross K-function, command *Kcross()* in the R package *spatstat*) was used, where j is the number of submissions within a certain distance of a media report i. A Monte Carlo simulation was applied to statistically test the distinction between the observed Cross K-function and a Cross K-function produced by random labelling, that is, all observations were labelled either as i = 'media report' or j = 'submission' while keeping the observed proportions (permutations = 100).

Attention economy (ii) and individual characteristics of citizen scientists and targeted communication (iii)

To identify possible factors influencing the attention and differences in participants' response rates, we followed three steps. First, we identified exceptional spikes in submission and media report numbers on a temporal scale by a descriptive analysis. Second, we related these findings to the proportion of geographical 'reach' categories. Third, we investigated the quality of headline and text of the dpa-release on June 6, 2016, that resulted in a maximum number of following media reports and submissions in comparison to the titles of all other dpa-releases from the dpa regional office of Berlin/Brandenburg. We paid attention to the language style as well as to the contextualisation, especially whether the latter is indicative of a specific event that could have prepared the ground for increased attention to mosquitoes.

Spatial differences and varying affectedness (iv)

We also investigated if differences in the response to media coverage on the level of federal states can be attributed to differences in the media coverage itself or to the degree to which people are affected by mosquitoes. We plotted numbers of submissions and media reports per federal state to identify possible contradictions. In an exemplary fashion, two contradictory federal states with high numbers of submissions but few media reports, and vice versa, were examined for whether there is a significant, quantitative difference in the reach of the respective media reports or in the media types, applying a Chi-square test of homogeneity. A qualitative evaluation of the media contributions per federal state, i.e. a text analysis, could not be carried out because most of the media reports were no longer accessible and therefore no statistically justifiable number of articles was available.

Media landscape (v)

To test whether media types may have different effects on the response rate of citizen scientists to the 'Mückenatlas', we analysed the submission forms filled by the participants and contrasted the results with the proportions of media types from the media clipping dataset. Each submission to the 'Mückenatlas' is required to be accompanied by a form filled out by the participant on which contact and collection details are provided: name, address, e-mail or phone number, collection date and site (if different from home address), and free remarks for collection-site description. In addition, an open question is raised on the submission form as to how the participants became aware of the 'Mückenatlas', with the examples 'internet', 'radio', 'acquaintances' and 'television' provided as possible answers (S1 File).

We selected 2098 submission forms of the year 2017 (approximately 10 % of total submission numbers to this date) with respect to the open question, as that year represents the most recent year of overlap with available data on media reports. Of these 2098 forms, 25.1% (n = 526) contained no response and were removed from the analysis. Of the remaining 1572 forms, 78 were considered invalid due to non-interpretable descriptions. To analyse the valid answers to the open question, they were manually binned to 'newspaper', 'magazine', 'television', 'radio', 'internet', 'personal communication', or 'other'. As the categorisation was conducted by one and the same person from the authors' collective, we waived the inter-observer reliability check.

All analyses were carried out with R, version 3.6.3 [59]. Datasets and plot figures were created using the R packages *ggplot2* [60], *tidyr* [61], *dplyr* [62], *scales* [63], and *zoo* [64]. Statistics were conducted with packages *rstatix* [65] and *tseries* [66]. For point pattern analysis, we deployed the packages *rgdal* [67], *raster* [68], *spatstat* [69], and *maptools* [70], while the colour scheme was created with *viridis* [71].

4. Results

4.1 Project awareness (i)

A comparison of the monthly numbers of submissions and of media reports over the considered time period (Fig 1a) shows that most peaks in media reports are concurrent with or followed by peaks in submissions. Figure 1b implies a time lag between peaks in media reports and submissions. Spearman cross-correlation analysis showed that the maximum correlation of $r_s = 0.677$ ($p < 0.001$) is at a value of $h = -1$, which means that most submissions occur about one month after a maximum of media coverage (Fig 1b).

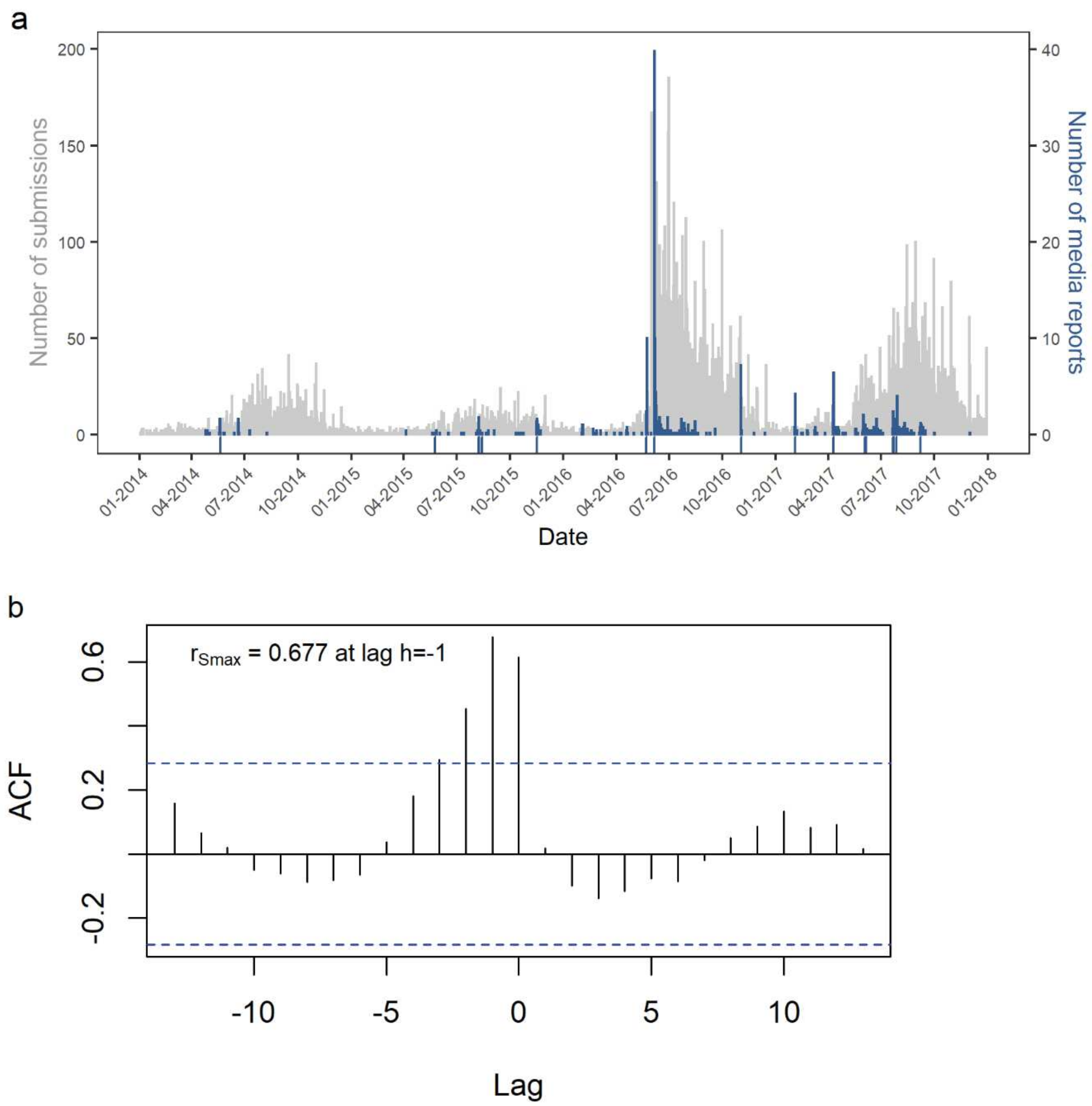

Fig 1. Temporal correlation of submissions of media reports between 2014 and 2017. (a) Combined plot of numbersof media reports (right y-axis) and submissions (left y-axis). The blue coloured ticks on the x-axis represent the dates of releases by the dpa regional studio Berlin-Brandenburg. Note the media echo and submission response to the dpa-release on June 6, 2016. (b) Cross-correlation analysis shows the highest value at -1, the blue dashed lines indicate a confidence threshold for α = 0.05.

The density plots show spatial aggregations of both 'Mückenatlas' submissions and media reports (Fig 2). Testing for complete spatial randomness of the individual datasets indicates that both point patterns are not randomly distributed, as for both comparisons of observed vs expected (theoretical homogenous Poisson process) patterns, cumulative distributions are significantly different (both $p < 0.01$). Both point datasets are clustered, as each observed curve lies above the theoretical Poisson process curve, and therefore empirical values are greater than theoretical values (S2 Fig).

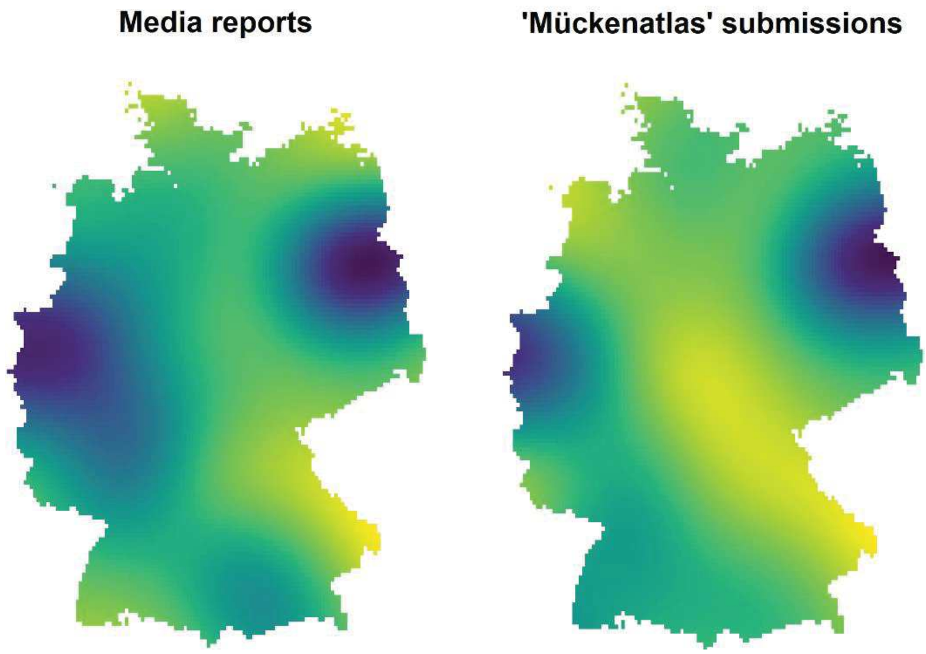

Fig 2. Density plots with gradients of spatial aggregation. The darker the colour, the more submissions or media reports, respectively.

Bivariate Ripley's K function output indicates that the locations of submissions are closer to the locations of media reports than complete spatial randomness would expect (S3 Fig). A Monte Carlo simulation with 100 permutations to test whether observed and theoretical mean curves were significantly different was run for distances up to 80,000 m. This procedure calculated an upper and lower simulation envelope for random labelling at a 99.98% significance level. The result implies attraction, indicating that the locations of media reports and 'Mückenatlas' submissions are closer together than would be expected under random labelling (S3 Fig).

4.2 Attention economy (ii) and individual characteristics of citizen scientists and targeted communication (iii)

Both patterns in Fig 1a display more media reports and submissions during the main mosquito season from May to September, compared to the autumn and winter months. Strikingly, over 50% of the reports were published in 2016 (n = 542), with an outstanding majority in June 2016 (n = 350, 37.5% of total reports). This suggests that an external factor positively affected the activation of participants. In 2017, submission and media report frequency kept to be high compared to 2014 and 2015, but not reaching the levels of 2016 (see S3 Table for annual numbers). A similar pattern can be seen in Fig 3: the distributions of geographical reach of media reports are more alike for 2014/2015 and 2016/2017. For the latter years, the amount of media reports with regional and single federal reach predominates.

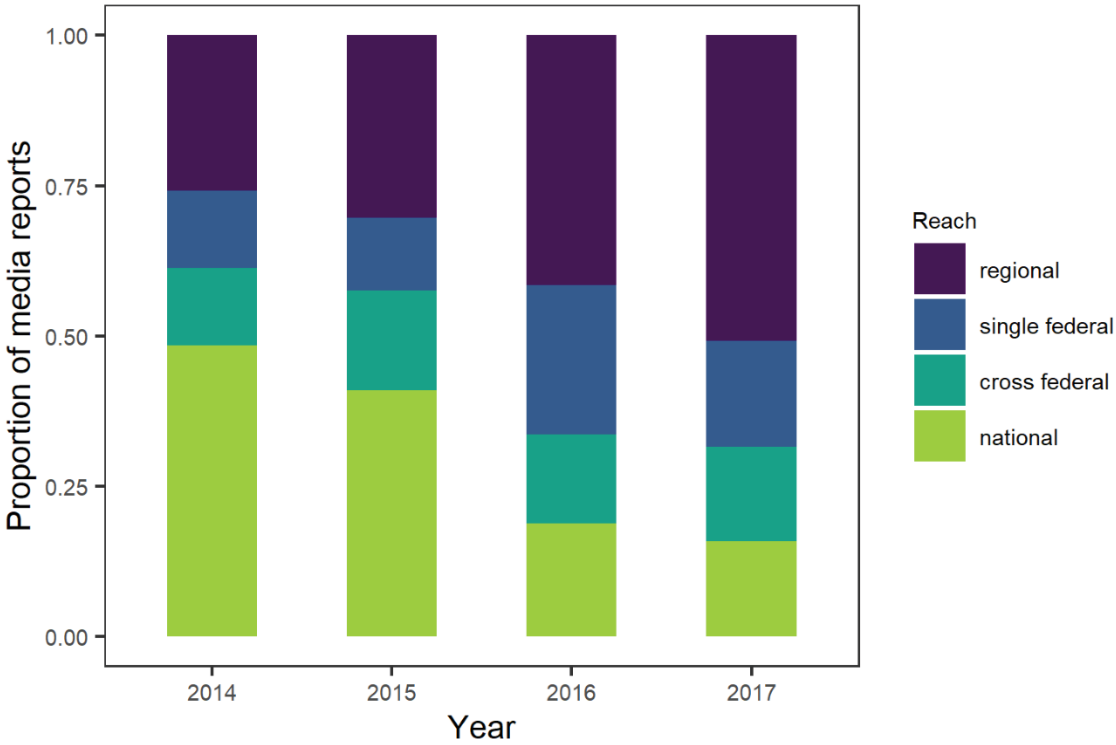

Fig 3. Annual proportions of geographical reach of media reports. While media reports with national reach predominated in 2014/2015, the share of regional and single federal category massively increased in 2016/2017.

The most successful dpa-release happened on June 6, 2016, and resulted in 199 media reports and a subsequent maximum in submissions on that very day (Fig. 1a). Therefore, we picked out this day to look at the headlines of the dpa-release as well as the media reports on that day and compared them to the headlines of all other dpa-releases. Most reports on that day had the same title as the original dpa-release:

> *Forscher-Bitte: Bürger sollen Mücken schicken / Researcher's plea: Citizens should send mosquitoes*

Also, some variations were used, but these all contained a concrete call-to-action similar to the dpa-release headline, such as:

Forscher: Schickt uns Mücken! / Researchers: Send us mosquitoes!
Bitte von Forschern: Mücken einfangen und einsenden / Request from researchers: Capture and submit mosquitoes
Bürger sollen Mücken fangen und einschicken / Citizens should catch and submit mosquitoes
Forscher: Schickt uns Mücken! / Researchers: Send us mosquitoes!

Opposed to that, dpa-release headlines outside that date did not appeal to the citizens for support (see S4 Table) in such a direct way:

Auch Mücken und Nacktschnecken lieben den Start-up-Sommer / Mosquitoes and slugs also love the start-up summer
Mückenatlas: Forscher fahnden nach neuen Stechmückenarten / 'Mückenatlas': Researchers search for new mosquito species
Biologin: Mückensaison bislang lau / Biologist: Mosquito season so far meagre
Jede Mücke zählt - Wie sich Exoten in Deutschland etablieren / Every mosquito counts - How exotics establish in Germany
Sommer, Sonne, Mücke - Plagegeister surren wieder / Summer, sun, mosquitoes - pests are buzzing again
Mückenjäger fangen 30 000 Tiere für die Forschung / Mosquito hunters catch 30,000 animals for resarch

By retrieving still existing online articles based on the dpa-release of June 6, 2016, and looking at the content, we found additional information why this release was followed by a high media echo and many submissions. An included quote from the project leader adopted by the media substantiates the call-to-action and places it in a timely context, namely with regard to the Zika virus epidemic that occurred in South America in 2016:

«Durch die in Europa in den letzten Jahren zunehmenden Ausbrüche von Stechmücken-übertragenen Krankheiten wie Dengue-, Westnil- oder Chikungunya-Fieber sowie den jüngsten Zika-Virus-Ausbruch in Südamerika wurde die aktuelle Bedeutung von

Stechmücken als Krankheitsüberträger unter Beweis gestellt», erklärte Walther. «Zur Risikoabschätzung benötigen wir dringend Daten zur Verbreitung der in Deutschland vorkommenden invasiven und einheimischen Arten.» /

"The increasing outbreaks of mosquito-borne diseases such as dengue, West Nile and chikungunya fever in Europe in recent years, as well as the recent Zika virus outbreak in South America, have demonstrated the current importance of mosquitoes as vectors of disease agents," Walther explained. "To assess the risk, we urgently need data on the distribution of invasive and native species in Germany".

4.3 Spatial differences and varying affectedness (iv)

In terms of spatial association of submissions and media report numbers aggregated by federal state, we found contradictory results. Most submissions do not necessarily come from federal states with high media coverage, e.g. Berlin (BE) or Hesse (HE), and a small number of media reports can as well result in high submission numbers, as observed in Baden-Wuerttemberg (BW) and Brandenburg (BB) (Fig 4).

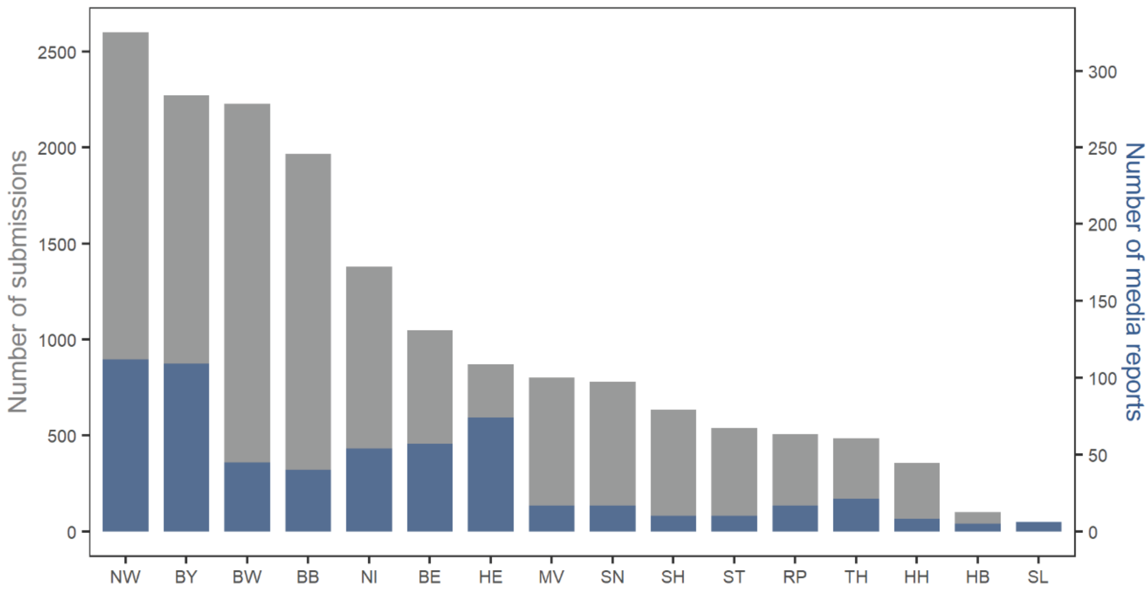

Fig 4. Numbers of submission (left y-axis) and media reports (right y-axis) by federal state. (NW = North Rhine-Westphalia, BY = Bavaria, BW = Baden-Wuerttemberg, BB = Brandenburg, NS = Lower Saxony, BE = Berlin, HE = Hesse, MV = Mecklenburg-Western Pomerania, SN = Saxony, SH = Schleswig-Holstein, ST = Saxony-Anhalt, RP = Rhineland-Palatinate, TH = Thuringia, HH = Hamburg, HB = Bremen, SL = Saarland). Spearman's correlation coefficient shows a highly positive correlation ($r_s = 0.878$, $p < 0.001$).

Focusing at the federal states of Baden-Wuerttemberg and Hesse as examples for reversed characteristics, the omnibus Chi-square test revealed no significant differences in the number of media types (*χ2* (1, n = 119) = 2.13, p > 0.05) or reach of media reports (*χ2* (1, n = 119) = 0.253, p > 0.05) (Table 1). Differences in participant responses must be traced back to either the quality of the media reports or the affectedness by mosquitoes.

Table 1: Number of media reports and outcome of chi-square test of homogeneity.

	Media type					
Federal state	*online*	*print*	*radio*	*television*	*χ2*	*p-value*
Baden-Wuerttemberg	26 (57.78)	7 (15.56)	7 (15.56)	5 (11.11)	2.13	> 0.05
Hesse	50 (67.57)	8 (10.81)	12 (16.22)	4 (5.41)		
	Reach					
Federal state	*Single federal*		*regional*		*χ2*	*p-value*
Baden-Wuerttemberg	32 (71.7)		13 (28.9)		0.253	> 0.05
Hesse	48 (64.9)		26 (35.1)			

Carried out for media type and geographical reach for the federal states of Baden-Wuerttemberg and Hesse, percentages are provided in brackets.

4.4 Media landscape (v)

According to the media clipping dataset about the 'Mückenatlas' from 2014 to 2017, most media reports were published online (n = 406, 43.3%), followed by radio broadcasts (n = 224, 24.0%), printed articles (n = 155, 16.6%), and television programmes (n = 152, 16.2%). By comparison, the evaluation of the submission forms showed that most participants became aware of the citizen science project 'Mückenatlas' online, followed by television, newspaper, radio, magazines, personal communication, and other sources (e.g. events, invited lectures at community colleges or health departments) (Table 2, Fig 5).

Table 2: Binned answers of the free-form response to the question "Where did you hear about the 'Mückenatlas'?"

Source	online	television	newspaper	radio	magazine	personal	other
n	576	346	255	230	146	129	41
%	38.6	23.2	17.1	15.4	9.8	8.6	2.7

The percentages refer to the number of submission forms including invalid answers (n = 1494). The number of individual answers exceeds the number of valid submission forms, since 11.9% (n = 205) of the participants named more than one source of information.

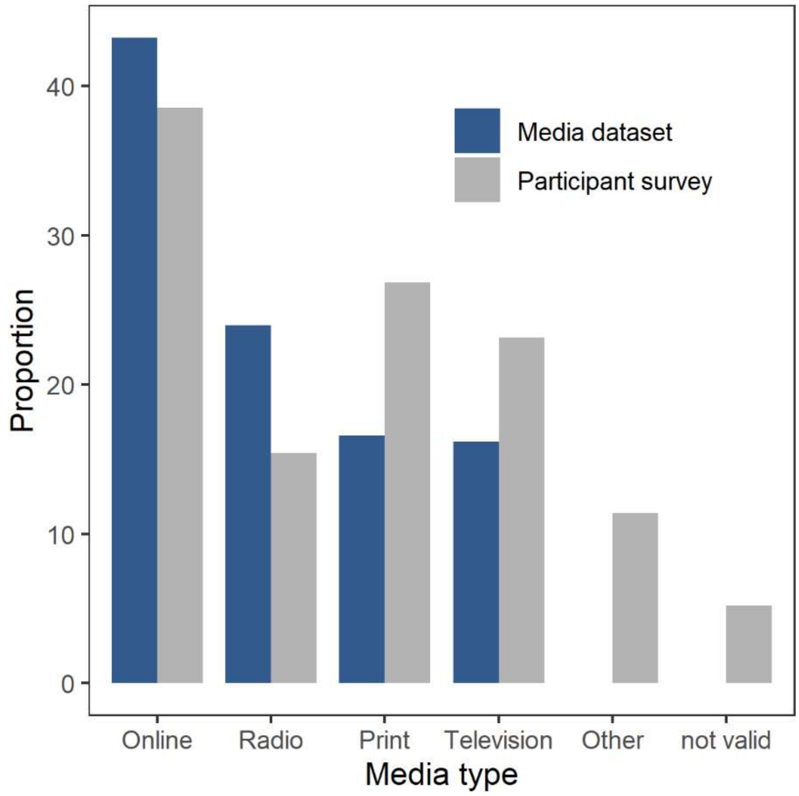

Fig 5: Comparison of the proportions of media types from the media clipping dataset and those from the participant responses. For the participant responses, the category 'print' also includes 'magazines'; the 'personal' category was assigned to 'other'.

5. Discussion

The 'Mückenatlas' is both a science communication and a research tool: information about mosquitoes is distributed to a broad public, and at the same time large amounts of data are collected for research. As participation does not require any skills or training – except for catching a mosquito without smashing it – the project counts on submissions from people who heard about the 'Mückenatlas' and rather spontaneously decide to take part. Therefore, we use mass media to reach the largest possible share of the population, because the more new participants submit mosquitoes, the more detailed the map of collections and the better the geographical coverage of Germany becomes. By investigating five influencing factors for the responsiveness to mass media communication events, we estimated how effective the 'Mückenatlas' mass media strategy actually is to reach the project's scientific goal.

5.1 Number of media reports impact submission frequency on a spatio-temporal scale (i)

Our assumption of a positive correlation between the number of media reports and the number of submissions was confirmed for both a temporal and spatial scale. Temporal associations between media campaigns and participants' activation have been attested before, e.g. a social media campaign and press release led to increased download and subsequent usage of an app for water body observation [43].

The time lag of around one month between the peak in media report and mosquito submissions could be an adaptive form of a typical response to citizens' exposure of a topic via mass media called *short-term fluctuation change* [58]: the media report induces a peak in knowledge and behavioural change that subsides after a couple of days. In case of the 'Mückenatlas', this time span might be extended a bit, as a mosquito is not always immediately available for catching but might still trigger the memory on the project a few weeks later.

The spatial analysis revealed that both point datasets are spatially clustered, with two hotspots of different sizes each in North Rhine-Westphalia (West Germany) and Brandenburg/Berlin (North-East Germany). Although the spatial distributions of the reports and submissions are not exactly the same, they are similar and locations of submissions are closer to the locations of media reports than would be expected by chance. Even if this connection seems logical, it has not yet been demonstrated in the context of citizen science. This finding highlights the potential of using the media to attract more records from underrepresented regions or areas of special interest through targeted communication of large-scale citizen science projects, such as approaching regional press or customising participation campaigns for local communities [40, 72].

5.2 Heightened attention to mosquitoes and a direct call for support maximises participation (ii-iii)

In addition to the positive correlation of numbers of media reports and submissions, Fig 1a shows repetitive temporal patterns and exceptional events. Both media reports and submissions underlie the seasonality of mosquito occurrence: the more mosquitoes there are, the higher the probability of someone participating and – presumably – the more they become an issue worth reporting. The fact that citizen observations and media reports reflect the phenology of the study object is a well-known phenomenon in citizen science projects for monitoring biodiversity [44, 73, 74]. Mosquitoes also make a popular topic in the summer slump, when politicians withdraw for vacation and themes to report on tend to be scarce. In general, Fig 1a also displays more media reports in 2016 and 2017 than in the previous years, which was mainly due to an increase in regional media reports (Fig 2) and is reflected by a high level in numbers of submissions throughout these years. The phenomenon emanates from a peak of media reports in June 2016 and could be explained by various factors.

First, the news [75] that the Zika virus is transmitted by mosquitoes and leads to brain damage in newborns if the mother has become infected during pregnancy had been picked up and spread by the German media in early 2016, thereby paving the way for greater attention to the relevance of mosquitoes for public health. Hence, in the context of the attention economy concept, the most successful dpa-release on June 6, 2016, had already the advantage of a heightened awareness to the topic.

Second, the style of the title of this dpa-release and those of the following media reports for which title information was available, was very distinct to that of all other dpa-releases by a concrete call to the public to submit mosquitoes. In addition, the text of the dpa-release, which was probably copied by many of the following media articles, included a quote by the project leader that related the importance of participation directly to the Zika virus. Chu et al. [40] reported a similar experience with a 2010 press release that combined a call for support and a researcher's quote about the scientific importance of people's participation in the citizen science project NestWatch. Moreover, health-related issues in connection with citizen science seem to be a very interesting topic for journalists in general [44]. In contrast, other dpa-release titles referred to a possible upcoming of severe mosquito plagues, how mosquitoes may react to predominating weather conditions, or, in some cases, to the invasion progress of alien species (S4 Table).

This triad of existing media attention towards mosquitoes, a direct appeal to citizens and relevance to health may have led to the maximum of submissions in June 2016. Continued strong coverage likely sustained public attention throughout 2016 and 2017, resulting in still high numbers of mosquito submissions. We assume that, additionally to a wider information reach also through regional media (Fig 2), the public's concern toward the Zika virus stayed high, which led citizens to use the 'Mückenatlas' as a tool of self-care, reassurance and as a communication channel to a trusted authority.

5.3 Many factors are responsible for regional differences in submissions (iv)

As assumed, regional differences in the response rate to media coverage could be identified. In accordance of the findings on the spatial correlation of the numbers of submissions with media reports, they also correlate positively on the federal state level. Despite this general correlation, the results are somewhat contradictory when having a closer look (Fig 4). For example, we picked out the federal states of Baden-Wuerttemberg and Hesse, with an inverse number of media reports and submissions, in order to find out whether this contradiction could be caused either by distinct proportions of media types/reach in each case or by differences in mosquito affectedness. Baden-Wuerttemberg is characterised by high submission numbers and low media reports, whereas the opposite is true for Hesse. Since there are no significant differences between media type and reach between the two federal states (Table 1), other factors might cause the contradiction.

Over a length of 420 km, the river Rhine borders Baden-Wuerttemberg with a multitude of riparian and floodplain areas and oxbow lakes. In addition, there are 155 km of shore area of Lake Constance. Warm and humid conditions and fluctuating water levels lead to regular mass developments of mosquitoes in these regions [76], which have been controlled by community organisations since 1910 [77]. In addition to this burden of mosquito nuisance on the human population, the invasive Asian tiger (*Aedes albopictus*) and Asian bush (*Aedes japonicus)* mosquitoes were detected in Baden-Wuerttemberg already in 2007 and 2008, respectively [78, 79]. By contrast, only 107 kilometres of Rhine with major breeding sites for mosquitoes is located in Hesse, where the first invasive mosquito species (*Ae. japonicus*) was only recorded in 2015 [36].

A reduced quality of life for many citizens due to nuisance, a long tradition of countermeasures, and prolonged media exposure of the impacts of invasive species may therefore have led to a higher affectedness by mosquitoes in the Baden-Wuerttemberg population. Hence, the willingness to participate in mosquito-related initiatives such as the 'Mückenatlas' might already have been on a relatively high level there and less dependent on media coverage. However, since 2017 a population of the invasive species *Aedes koreicus* has been occurring in Wiesbaden, Hesse, as the only population in Germany [80]. Whether the accompanying media coverage has a direct impact on the number of submissions from this federal state should become an interesting study object in the coming years.

Another interesting pattern was that, similarly to Baden-Wuerttemberg, the federal states of Mecklenburg-Western Pomerania (MV) and Brandenburg (BB) showed high submission frequencies despite low numbers of media reports (Fig 4, see also [81]). This pattern resulted from a *headquarter effect*, meaning that local communities tend to support their local projects, also known as place-based effects [82].

5.4 Different media types have different effects on citizen responsiveness (v)

More than 85% of all participants whose responses were analysed learnt about the 'Mückenatlas' through a media channel, thereby highlighting the effectiveness of the project's communication strategy, as millions of people are reached via mass media per year [44]. However, there are disparities between the proportions of media types that reported on the 'Mückenatlas' and the channels through which participants learned about the project. Print media and television are only moderately used to report on the 'Mückenatlas', but obviously have an activating effect. Typical television broadcasts that feature the citizen science project are science-related programmes and regional news formats. Print media is still an important source of news on the regional level [83, 84], and the probability that local newspapers report on the 'Mückenatlas', e.g. in the context of a local nuisance or an invasion incidence [73], is higher than with national print media.

Although online media seem to be the most effective way of raising awareness of the 'Mückenatlas', our results can barely be interpreted due to the lack of comparability of the participants' response and the media clipping dataset. The 'online' category of the media clipping dataset comprises everything from internet-representations of print, television, and radio media to pure e-zines to forums. On the other hand, what is behind the 'online' category based on the participant answers remains in the dark for the time being, as only a few of them provided more information than 'the internet'. This is probably also due to the fact that 'internet' is listed as an answer example in the question on the submission form, and thus had a suggestive effect. In addition, this category probably covers much more than that of the media clipping dataset, because the 'Mückenatlas' homepage, social media, or e-mails could also be meant. Radio has the least impact on potential participants, as it appeals to only one sense and is consumed more fluctuating, but also more in passing. Although we cannot derive any evidence-based explanations for these disparities, the results confirm the findings of other studies that different types of media have different effects on participation [23, 41, 43].

The fact that word-of-mouth propaganda ('personal'), although minor (7.5%) and not supported by marketing, still takes place shows parallels to recruitment processes known from the volunteering literature [85]. Face-to-face communication is another important factor to recruit participants, e.g. at events, especially to reach a more diverse group of participants [86].

5.5 Limitations

There are some shortcomings to this study, mainly based on the media clipping dataset. First, there is a lack of online data for 2017, as the institute changed the clipping service for online media. We decided against including a separate dataset from the new service, as it is based on different search algorithms and search terms, making comparisons unfeasible. In addition, print media data is missing for 2014 to 2016, which could skew the dataset towards an over-representation of regional reach in 2017. The spatial distribution of submissions is biased by human population density [81]. However, the number of media houses, and therefore of newspapers, broadcasters, and websites, underlie the same effect: in general there are more media in more densely populated areas.

The qualitative title and text analysis is based on dpa-releases, as these trigger the majority of media reports with mostly the same or very similar wording. However, there are also a considerable number of media reports that are independent of these dpa-releases. This information was excluded in the qualitative analysis. In order to make a more reliable statement on spatial and temporal effectiveness in connection with text quality, the inclusion and retrieval of all articles would be necessary. Future studies could use experimental approaches with differently designed press or dpa-releases to test our findings and assumptions.

6. Conclusions

The clear positive correlation between numbers of media reports and numbers of mosquito submissions demonstrate that communication of the project via the mass media as multipliers is important to activate participants. However, the resulting temporal and spatial clustering of the submissions is also a potential source of bias in opportunistically collected data. This has been observed in other studies [87, 88], but has never been investigated specifically in the context of citizen science. We suggest that data bias induced by media coverage should be further explored in the future.

In times when public attention is a scarce commodity, the title of a media report can be a decisive hook. With a targeted call-to-action in the title, we achieved maximum participation and, rather unintentionally, took advantage of increased media and public attention due to a current human health risk situation caused by mosquitoes. Since other projects have also made this experience [40], it could be a good indication how to design catchy titles for press releases or newsletters. In addition, issue management in the sense of horizon scanning is worthwhile to optimise the timing of communication activities [44].

Despite the clear spatial association between media reports and submissions on a national level, differences in regional participation frequency are presumably due to multiple factors. For mosquitoes, we could demonstrate that human affectedness might play an important role. The level of affectedness towards the subject of interest could therefore be also used in a more targeted way, e.g. appeal to pet owners to collect ticks or to hobby gardeners to monitor invasive environmental weeds.

We suggest to involve the media and establish reliable relations with press representatives already when planning new or reinvigorate existing citizen science projects [89]. For example, the ZALF 'Mückenatlas' project lead maintains good connections to the regional dpa-office representing Berlin and Brandenburg. The co-operation works mutually: we can approach them, e.g. when submission frequency is low, and they can contact us whenever an expert for mosquitoes is needed. Continuous communication via the media is particularly recommended and important for projects that aim to achieve a large and finely granulated spatial coverage over a considerable period of time in order to continuously attract new participants and to remind citizens who have already been contributing. This is especially true for projects that rely on contributions from 'dabblers' [90] and do not require participant training or the provision with certain equipment.

However, the media can only be the spark that triggers pre-existing intrinsic and extrinsic motivational factors of the citizens, which need to be investigated in further studies. Knowing more about the demographic background and motivations of the citizen scientists would allow for customised marketing campaigns that might lead to constantly higher numbers of submissions compared to an undifferentiated 'scattergun approach' via the mass media [39].

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Data availability statement

The datasets used for analysis are provided via the Open Research Data repository at the Leibniz Centre for Agricultural Landscape Research (ZALF), Germany, https://www.doi.org/xx.xxxx/ZALF.DK.xxx. The dataset of the 'Mückenatlas' submissions does not contain the geo-locations as the publication would violate the personal privacy of the citizen scientists.

Supporting Information

S1 Fig: Impressions from the workflow of the 'Mückenatlas'. (a) During the mosquito season, the submissions arrive in boxes (Photo: Nadja Pernat/ZALF). (b) The participants are very creative in packing the samples (Photo: Nadja Pernat/ZALF). (c) Every mosquito sample is identified to species level and uploaded to the German database for Culicid research (Photo: Jarno Müller/ZALF). (d) Well-preserved and special finds are kept in a reference collection (Photo: Jarno Müller/ZALF). (e) The submission counter on the homepage www.mueckenatlas.com informs about the progress. (f) Every participant who wants to gets a marker with a name or pseudonym on the collector's map on the website.

S2 Fig: Plotted results of the Kolgomorov-Smirnov test. Based on Kernel density of geo-references as spatial covariate for (a) media reports and (b) submissions, indicating a non-random distribution of both point pattern datasets across Germany. Ripley's K function suggests a clustering of both point patterns, for (c) media reports and (d) 'Mückenatlas' submissions (right column). As the number of points for the submission dataset exceeds 3000, only border correction estimations (no edge effects) could be calculated for (d).

S3 Fig: Cross K-function and Monte Carlo simulation. (a) Bivariate Ripley's K function (Cross K-function) testing for similar clustering of media reports and submissions for distances up to 80 km. b) Cross K-function (black line) with simulation mean (red dashed line) and significance bands (grey area) for random labelling applying a Monte Carlo simulation with 100 permutations.

S1 Table: List of variables of the media clipping dataset. Original variables (renamed) are highlighted in white and additionally programmed variables for analysis are highlighted in grey.

S2 Table: Categorisation method.

S3 Table: Annual numbers of media reports and submissions.

S4 Table: Headlines of the Berlin/Brandenburg office dpa-releases used for qualitative analysis. The clipping service sometimes recorded a dpa-release several times in one day, the number of these duplications are enclosed in brackets. Daily previews announcing dpa-releases were not included.

S1 File: Submission form. This template is available for download at www.mueckenatlas.com and in paper form on request at the project office (German only).

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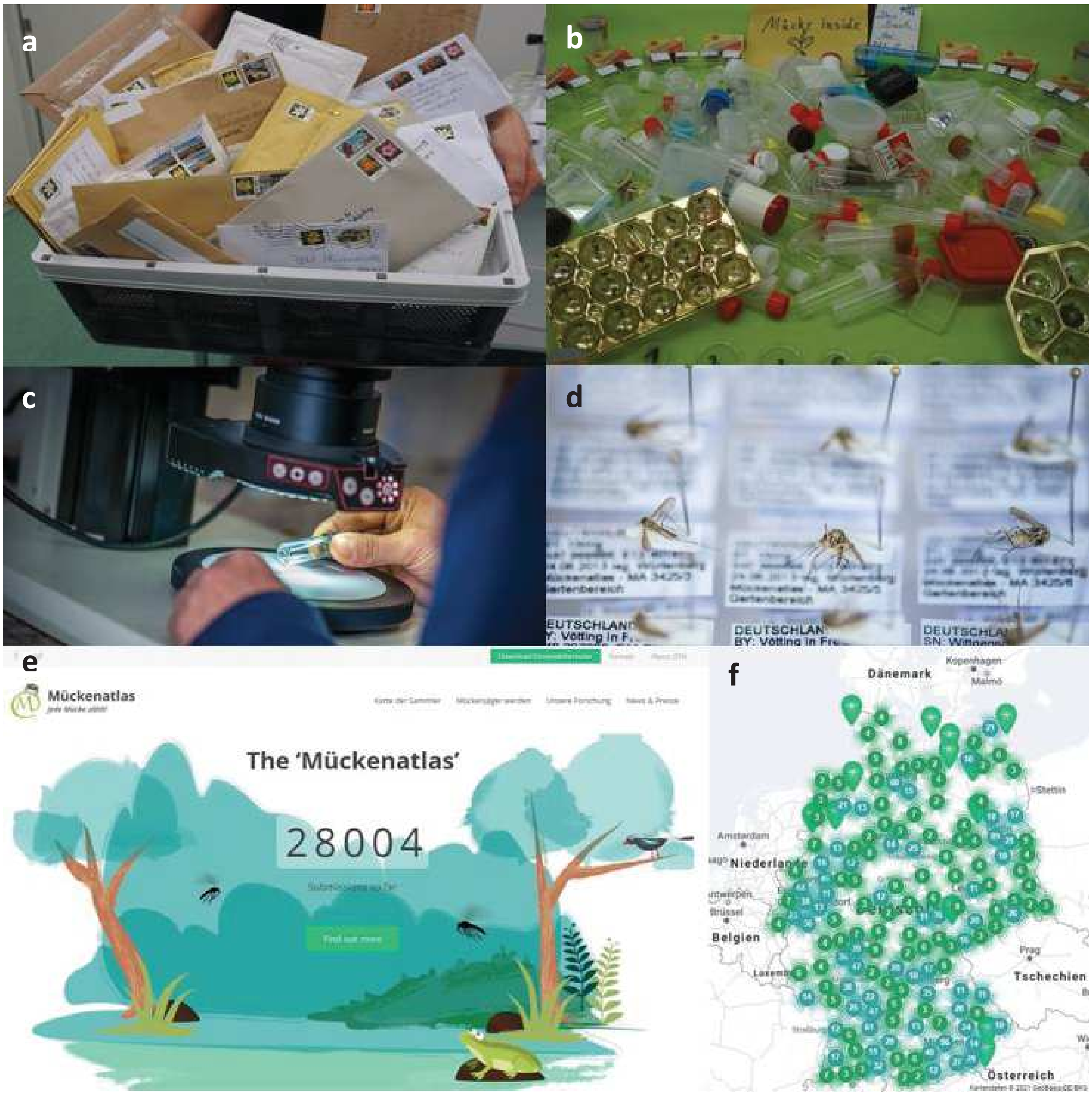
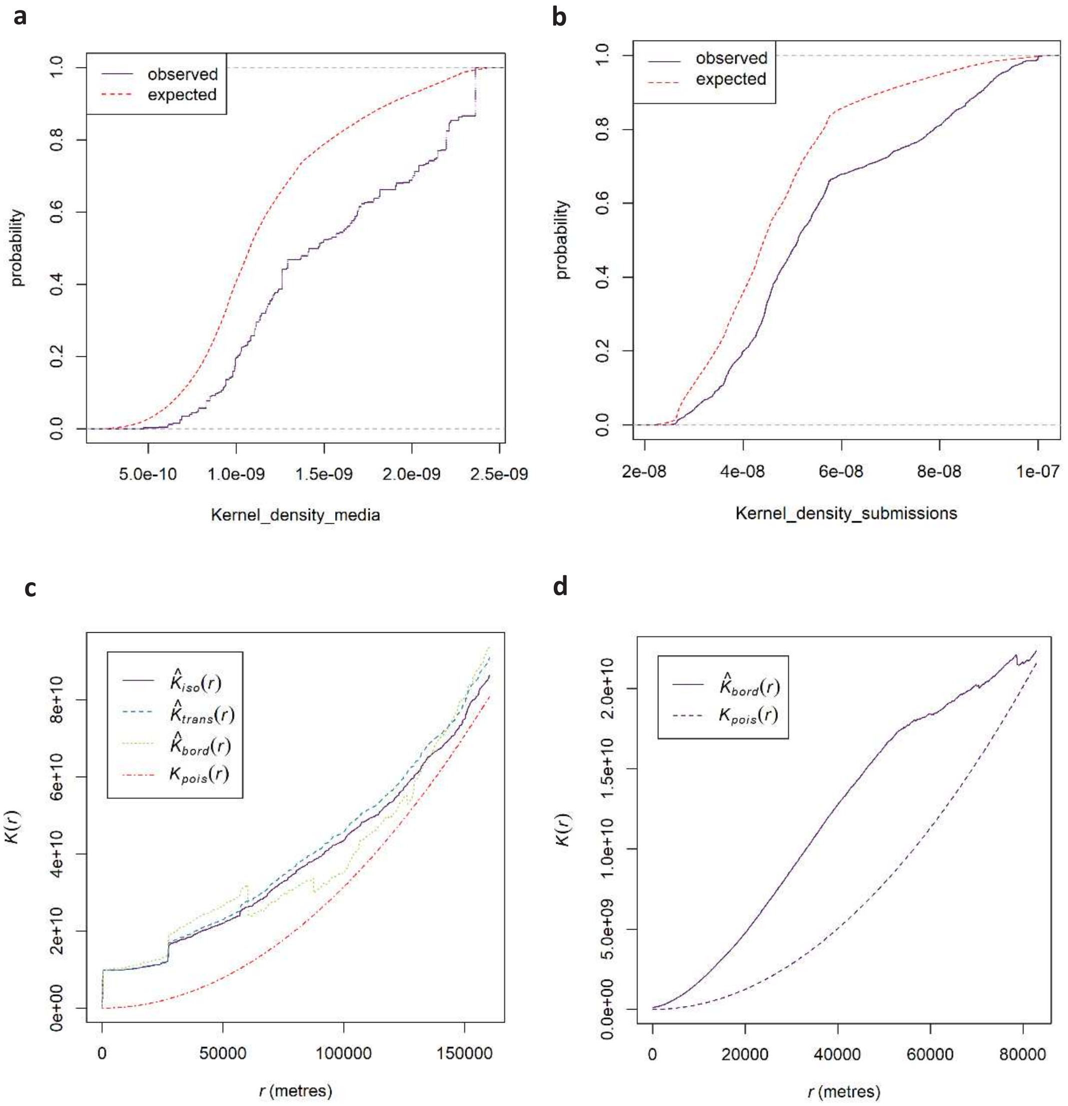
Appendix: Supporting Information Chapter 5

S1 Figure



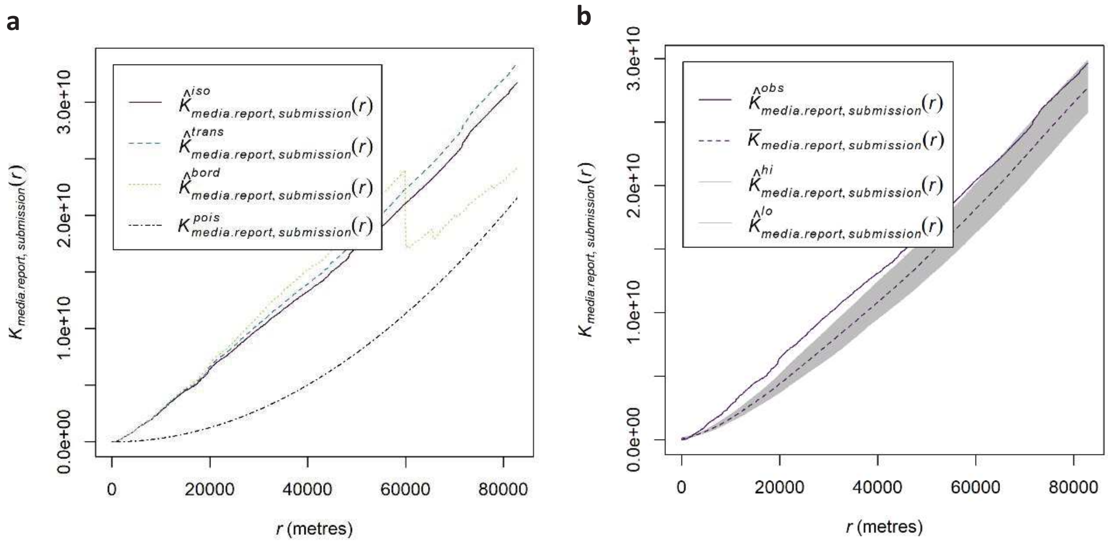
S1 Fig: Impressions from the workflow of the 'Mückenatlas'. (a) During the mosquito season, the submissions arrive in boxes (Photo: Nadja Pernat/ZALF). (b) The participants are very creative in packing the samples (Photo: Nadja Pernat/ZALF). (c) Every mosquito sample is identified to species level and uploaded to the German database for Culicid research (Photo: Jarno Müller/ZALF). (d) Well-preserved and special finds are kept in a reference collection (Photo: Jarno Müller/ZALF). (e) The submission counter on the homepage www.mueckenatlas.com informs about the progress. (f) Every participant who wants to gets a marker with a name or pseudonym on the collector's map on the website.

S2 Figure



S2 Fig: Plotted results of the Kolgomorov-Smirnov test. Based on Kernel density of geo-references as spatial covariate for (a) media reports and (b) submissions, indicating a non-random distribution of both point pattern datasets across Germany. Ripley's K function suggests a clustering of both point patterns, for (c) media reports and (d) 'Mückenatlas' submissions (right column). As the number of points for the submission dataset exceeds 3000, only border correction estimations (no edge effects) could be calculated for (d).

S3 Figure



S3 Fig: Cross K-function and Monte Carlo simulation. (a) Bivariate Ripley's K function (Cross K-function) testing for similar clustering of media reports and submissions for distances up to 80 km. b) Cross K-function (black line) with simulation mean (red dashed line) and significance bands (grey area) for random labelling applying a Monte Carlo simulation with 100 permutations.

S1 Table: List of variables of the media clipping dataset. Original variables (renamed) are highlighted in white and additionally programmed variables for analysis are highlighted in grey.

Provided variables	**Explanation**
Search terms (searcht)	Search term responsible for the hit
Publication date (date)	Exact date of media report
Headline (head)	Headline of the media report
Format (rad.tv)	Premiere or rerun
Link	URL to online media type
Media title (med.tit.cat)	Title of newspaper, radio or tv programme
Channel (med.ch)	Name of media channel (e.g. broadcaster of tv/radio show)
Media type (med.ty.cat)	Category of media ('TV', 'online', 'print', 'radio', 'news agency')
Media category (med.ty.fine)	Refined media type (e.g. for TV documentary, news etc.)
Additionally programmed variables	
year	Year of media report
yearm	Year and month of media report
Municipality (med.muni)	Municipality of origin (see Supplementary Table S2)
xvalue	Longitude if municipality is given (see Supplementary Table S2)
yvalue	Latitude if municipality is given (see Supplementary Table S2)
Federal state (med.county)	Federal state of origin if applicable (see Supplementary Table S2)
Reach (reach)	Geographical reach ('regional', 'single federal', 'cross federal', 'national') (see Supplementary Table S2)

S3 Table: Annual numbers of media reports and submissions

Year	Media reports	Submissions
2014	31	1903
2015	66	1221
2016	542	7756
2017	295	5730

S4 Table: Headlines of the Berlin/Brandenburg office dpa-releases used for qualitative analysis. The clipping service sometimes recorded a dpa-release several times in one day, the number of these duplications are enclosed in brackets. Daily previews announcing dpa-releases were not included.

dpa-release headline (in German)	Release date
Auch Mücken und Nacktschnecken lieben den Start-up-Sommer (2)	20.05.2014
Sommerstart auch für Mücken und Nacktschnecken	20.05.2014
Mückenatlas: Forscher fahnden nach neuen Stechmückenarten	25.05.2015
Biologin: Mückensaison bislang lau - «Ohne Wasser keine Mücken»	08.08.2015
Biologin: Mückensaison bislang lau - «Ohne Wasser keine Mücken»	09.08.2015
Beißen und Stechen - Welche Tiere im Sommer besonders nerven	14.08.2015
Jede Mücke zählt - Wie sich Exoten in Deutschland etablieren	16.11.2015
2015 war kein Mückenjahr - Weniger Einsendungen für den Mückenatlas	16.11.2015
Sommer, Sonne, Mücke - Plagegeister surren wieder	23.05.2016
Verdächtiges Surren: Mücken fliegen wieder	23.05.2016
Forscher-Bitte: Bürger sollen Mücken schicken	**06.06.2016**
Mückenplage droht - Bürger sollen Exemplare einschicken (3)	**06.06.2016**
Mückenforscher freuen sich über so viel Post wie nie zuvor	02.11.2016
Mückenjäger fangen 30 000 Tiere für die Forschung	02.11.2016
Mückenforscherin kartiert die kleinen Plagegeister	03.02.2017
33 500 Mücken und noch lange kein Ende	03.02.2017
Sie sind schon da: Sonniger Frühling lässt Mücken eher ausschwärmen	10.04.2017
Stechende Plagegeister - warmer Frühsommer gut für Mücken	03.06.2017
Surren und Stechen: Warmer Frühsommer ist für Mücken ideal	03.06.2017
Surren und Stechen: Warmer Frühsommer ist für Mücken ideal	05.06.2017
Nach dem Regen: Hochsaison für Mücken	22.07.2017
Expertin zur Mückenplage	22.07.2017
Das große Surren - alle zwei Wochen neue Mückengeneration	22.07.2017
Expertin zur Mückenplage	23.07.2017
Das große Surren - alle zwei Wochen neue Mückengeneration	23.07.2017
Sommer 2017 ist ideal für Mücken und schlecht für Wespen	28.07.2017
«Die Mücken schreien hurra» - ideale Bedingungen nach Regenflut	28.07.2017
«Mücke tobt überall» - Nahender Herbst treibt Hausmücken in Verstecke	07.09.2017
«Es ist die Hölle»: Nahender Herbst treibt Stechmücken ins Haus	07.09.2017

S1 File: Submission form. This template is available for download at www.mueckenatlas.com and in paper form on request at the project office (German only).

Mückenatlas

Einsendeformular

* Pflichtangaben

Absender	
Name*	**Straße, Hausnummer***
	PLZ, Ort (ggf. Ortsteil)* Beispiel: 16866 Kyritz oder 16866 Kyritz OT Holzhausen
E-Mail-Adresse (bitte geben Sie die E-Mail-Adresse für eine Rückantwort an)	Sollen Angaben zu Ihrer Person bei Ihrem Fundort auf der Karte der Sammler auf www.mueckenatlas.com gemacht werden? Bitte kreuzen Sie an. * **Ja** **Nein** Falls ja, in welcher Form? * (Beispiel: Name, Initialen, Pseudonym)
Telefonnummer	
Wie sind Sie auf den Mückenatlas aufmerksam geworden? (Beispiel: Internet, Funk, Bekannte, Fernsehen o.ä.)	

Ort und Zeit des Fundes * (bitte nur angeben, wenn von oben abweichend)		
Straße, Hausnummer	**Geokoordinaten (z.B. von google maps)**	**Fangdatum**
PLZ, Ort (ggf. Ortsteil)		
Weitere Einzelheiten zum Fundort (z.B. Wald, Wiese, Garten, Keller, Wohnzimmer o.ä.)		

Damit wir Ihre Daten verarbeiten können, erklären Sie sich bitte durch Ihre Unterschrift mit der rückseitigen Datenschutzerklärung einverstanden.

X Datum, Unterschrift

Leibniz-Zentrum für Agrarlandschaftsforschung
„Mückenatlas"
Eberswalder Str. 84m
15374 Müncheberg

Bitte senden Sie Ihre Post an links stehende Adresse:

Chapter 6 | General discussion

Citizen science is an emerging scientific discipline with still many unknowns, whose presumed positive impact on science and society is only gradually being discovered. Citizen science programmes in ecological and environmental sciences make up a large part of the worldwide projects. The data collected in these programmes have already been used – visibly or invisibly – for numerous publications (Cooper, Shirk and Zuckerberg, 2014; Kullenberg and Kasperowski, 2016). Because these citizen science projects are so multifaceted (Pocock et al., 2017), there is a lack of clarity about the strengths and weaknesses of the approaches, how to analyse the data without drawing false conclusions due to possible biases, and how outreach activities impact participant responsiveness and thus data collection processes.

The general aim of this work was to assess the contributions of the 'Mückenatlas' data collection to mosquito research in Germany. My research was structured into three work packages: *Method*, *Data*, and *Outreach*, reflecting issues currently being discussed in the academic community. In these work packages, I compared the performance of the 'Mückenatlas' approach to a conventional, professional monitoring method (Chapter 2), evaluated the opportunistic data collection for its usability for ecological research (Chapters 3 and 4), and investigated the influence of media coverage of the 'Mückenatlas' on participation and data structure (Chapter 5) (Figure 5).

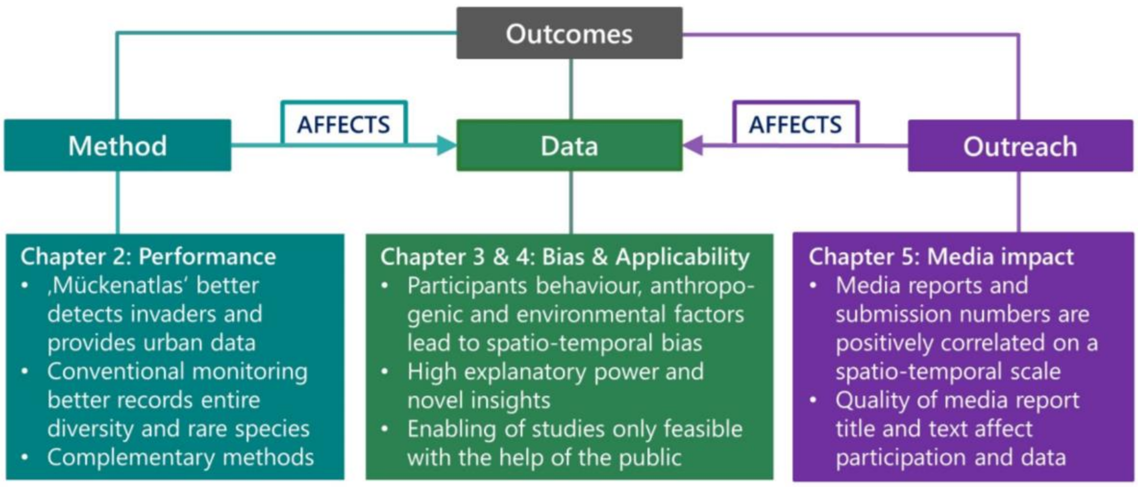


Figure 5: Synthesis of the main outcomes per work package.

6.1 The ‘Mückenatlas’ compensates for the weaknesses of active monitoring

In Chapter 2, the data collected by ‘Mückenatlas’ participants (*passive monitoring*) were compared with data from conventional sampling with BG-Sentinel traps by scientists (*active monitoring*) in systematic field work approaches. As parameters for this comparative study, coverage of land use types, species discovery by time and sites, species richness, and the capability to detect invasive species were selected. These parameters allowed for a quantitative comparison of both monitoring approaches with a focus on species. The objective of this study was to identify potential weaknesses and strengths of either method and to generally assess the performance of the ‘Mückenatlas’ as a component in Germany’s mosquito monitoring programme.

Only in species discovery over time did we[1] find little difference between the methods. Looking at species discovery by sites, however, the ‘Mückenatlas’ needed around 15 times more locations than *active monitoring* to reach the respective species richness. This difference is explained by the theoretical capability of a BG-Sentinel trap to capture thousands of specimens within 24 hours (Lühken et al., 2014). In contrast, citizens usually collect only one mosquito for the ‘Mückenatlas’. However, the many sampling sites of *passive monitoring* result in much finer-grained coverage of Germany than would be possible with traps, whose number of locations is limited by human and financial resources.

A finer spatial resolution and higher coverage over a large scale is often highlighted as a major advantage of citizen science (Devictor et al., 2010). However, when considering the disproportions in the distribution of land use types resulting from the locations of submissions, the question arises how useful the higher spatial coverage really is. The ‘Mückenatlas’ samples, for example, mainly stem from populated areas, from inside the homes or gardens of the participants. This confirms findings by other studies that opportunistically collected data are not representative of the actual proportion of land use types in the respective sample area (Geldmann et al., 2016; Tiago et al., 2017). In the case of the ‘Mückenatlas’, however, the duality of the project makes the difference: although it is originally a biodiversity programme, it differs from other approaches in Germany, such as butterfly (Richter et al.,

[1] By *we* is meant the respective entire authorship of the study to which the sentence refers. The authorship consists of the co-authors as specified in section IV: List of publications, and the first author, who is also the author of this cumulative thesis. This applies here and in the further course of the General discussion.

2018) or bird (Randler, 2021) monitoring, in that the study object is also relevant to public health. That makes the data trade-off between large spatial coverage and overrepresentation of populated areas actually valuable for mosquito research. Private properties are inaccessible to scientists, so there is a lack of crucial information on species biodiversity in areas of human settlements (Spear, Pauly and Kaiser, 2017). However, this information makes it possible to study the impact of urbanisation on population dynamics (Townroe and Callaghan, 2014) and thus improve risk assessments for mosquito-borne disease outbreaks. For example, mosquito occurrences and population dynamics could be fed into epidemiological models, as done by Kain and Bolker (2019) with *eBird* data to predict West Nile virus transmission. Lastly, the overrepresentation of data from populated areas enables to address research questions about the indoor mosquito biome (see Chapter 6.3).

Unlike other biodiversity citizen science projects where citizens seize the opportunity to go to places that attract them, such as green spaces or nature preserves to monitor birds or plants (Millar et al., 2018; Johnston et al., 2020), 'Mückenatlas' participants apparently prefer to catch a mosquito at home. Although there is evidence that programmes are particularly popular when data collection can be done at home (Catlin-Groves, 2012), the 'Mückenatlas' does not specifically invite to do this. So why do so many people collect mosquitoes inside their home and gardens, except for convenience? The differences in species recordings of both methods may provide answers.

In comparison, *passive monitoring* recorded less species richness than *active monitoring*, but detected all six invasive mosquito species currently documented for Germany. In addition, first detections of the most common invaders, *Ae. japonicus* and *Ae. albopictus*, in the respective federal states also took place mainly through the 'Mückenatlas'. One reason for the better detection capability of *passive monitoring* could be the higher number of submissions from densely populated areas: on the one hand, cities are entry points for invasions due to international travel and trade (Gaertner et al., 2017). On the other hand, most invasive mosquito species are well adapted to human settlements and readily breed in artificial containers (Wilke, Benelli and Beier, 2020). However, the disproportionately high number of submissions of native mosquitoes that look similar to invasive species in the eye of the participants (e.g. *Aedes geniculatus* or *Culiseta annulata*) indicates that citizens are more likely to be on the lookout for invasive species. This increases the probability of actually catching a non-native mosquito. As this association is confirmed by other projects (Roy et al., 2015; Vaux and Medlock, 2015), the outcome suggests that people participate in the 'Mückenatlas' to make sure that one's home is not infested by any invasive mosquito. Consequently, the taxonomic bias towards species that 'resemble' invaders might be caused by the participants' selective behaviour.

In *active monitoring*, the deliberate placement of traps according to the proportion of land use types in Germany leads to a higher species richness. In addition, a different species composition was found compared to *passive monitoring*, mainly due to the fact that several rare species were collected. There are contradictory results on species richness in the citizen science literature, where it is either the same (Braz Sousa et al., 2020) or predominates in professionally collected (e.g. Soroye, Ahmed and Kerr, 2018, for butterflies) or citizen science data (Callaghan et al., 2018, for birds). However, in these studies species composition also differs per approach, which indicates that the choice of method has a decisive influence on which species are recorded. For the formal mosquito monitoring in Germany, this means that the *active monitoring* approach is more suitable for a systematic inventory of mosquito diversity and for small-scale, in-depth studies on the ecology of individual mosquito species.

In sum, *active monitoring* performed better in recording the entire mosquito diversity and needed less locations and samples, whereas the citizen science approach (*passive monitoring*) showed a better ability to detect invasive species and provided data from private properties normally inaccessible to scientists. The different set of mosquito species detected with both approaches added up to the 52, reliably detected species in Germany (Werner, Kowalczyk and Kampen, 2020) – underlining how well the two methods complement each other. Chapter 2 thus allows the conclusion that *active* and *passive monitoring* compensate for each other's weaknesses and bring their own strengths to the monitoring programme.

6.2 Causes of bias in the 'Mückenatlas' opportunistic data

Chapter 3 presented an exploratory approach to identifying characteristics and causes of bias in the opportunistically collected data. The temporal analysis on yearly and monthly variation in submission numbers was carried out with descriptive methods, whereas a specific model computed the effects of anthropogenic and environmental variables on the spatial distribution of submission counts and probability. The results may inform future users about what biases to expect when working with opportunistic datasets by specifying the main drivers of variation in submissions.

Overall, the ‘Mückenatlas’ dataset is characterised by strong temporal and spatial biases. Only the monthly variation is likely to occur also in professional monitoring data. It reflects the activity period of mosquitoes in Germany, with higher numbers of recordings from May to September. Usually, in arthropod biodiversity citizen science projects, the observations reflect the phenology of the target species (Curtis-Robles et al., 2015; Porter et al., 2016; Prudic et al., 2017). However, winter activity recorded by the ‘Mückenatlas’ is also indicated in the form of submissions of hibernating specimens detected by humans. This mirroring of mosquito phenology would also be evident with other monitoring methods – except for winter activity, as *active monitoring* is normally interrupted for this season – and is therefore less of a unique feature of the opportunistic dataset.

While the pattern of submissions by month is subject to mosquito phenology, the strong fluctuation of submissions from year to year is not so readily explicable. The descripttive analysis allows only few conclusions to be drawn, leaving room for speculation about the causes of these fluctuations. For example, climatic conditions can lead to a mass development of mosquitoes (Roiz et al., 2015), increasing the likelihood of encountering one by a citizen. This may have been the case in the years with the most submissions, 2016 and 2017. However, with the prior knowledge from Chapter 2, where recording behaviour was already implicated to bias the species composition in the ‘Mückenatlas’ data, it was natural to assume that recording behaviour also influences the annual fluctuations in the submission numbers. Wouldn't it be more likely that a specific event caused the German population to participate more in the 'Mückenatlas' than that a favourable weather constellation in different regions increased the probability of a mosquito encounter? As a plausible trigger we identified the ZIKA epidemic in South America in 2016. This event generated a lot of media attention and simultaneous coverage on the 'Mückenatlas' in corresponding media reports (see Chapters 5 and 6.4). Driven by this topicality and by a higher level of awareness of the citizen science project, people may have participated more. Comments on the reporting forms during this period also suggest great concern among participants about harbouring a non-native species that can transmit the Zika virus.

The preparation of the data for the spatial pattern analysis showed that the raster map of submissions counts across Germany resembled a human population density map. This spatial pattern was expected as it is common in opportunistically collected data (de Coster et al., 2015; Leandro et al., 2020), and therefore human population density was pre-selected for our model. But instead of just including this effect in the model, as has been done in other studies, it was additionally investigated whether there was another, hidden pattern when population density was factored out. Indeed, a map of per-capita submissions per grid cell revealed regions with high engagement regardless of population density, especially near the project offices. Possibly, people within a certain distance to the institutes responsible for the 'Mückenatlas' are more engaged or more likely to know about the project. I proposed in Chapter 3 to call this phenomenon the *headquarter effect*, as a specific manifestation of the *power of place* effect, described by Newman et al. (2017) as the connection of communities to their region based on emotion or culture.

To investigate drivers of spatial variation in submissions, human population density and further anthropogenic (female proportion, location in political former East Germany) and environmental predictors (precipitation, presence of water bodies and wind speed) were included in a hurdle model. The hurdle model fitted best the overdispersed and zero-inflated count data and allowed for both counts and probability of submission to be taken into account (Cragg, 1971; Mullahy, 1986). The results clearly demonstrated which factors positively or negatively affect the counts or the probability of a submission, but the interpretation of the effects found was nevertheless complex. Many of the predictors not only cause the biases directly, but also influence the behaviour of the participants. Even by dividing the variables into anthropogenic and environmental predictors to decide whether these have more impact on the participants or on the mosquitoes, there are plausible explanations from both sides. For example, the negative correlation of precipitation with submission numbers could indicate drier regions in north-eastern Germany, where many natural breeding sites favour mosquito development. On the other hand the negative correlation could result from increased artificial irrigation due to little rainfall, which leads to reliable water sources for mosquito breeding created by citizens (e.g. plant saucers).

This interdependence of anthropogenic and environmental predictors with the recording behaviour of the participants is in stark contrast to professional data collection. In the best case, the scientists' collection behaviour is independent of external influences and therefore effects from biotic and abiotic factors can be interpreted more clearly. In global terms, however, professional scientists produce data that is heavily skewed both taxonomically and geographically (Tydecks et al., 2018; Stephenson and Stengel, 2020).

Chapter 3 revealed the spatial and temporal bias inherent in the data. This sets the stage for further use of the opportunistic dataset for mosquito research beyond occurrence maps. In a next step, approaches for the application of biased citizen science data could be derived from the rapidly growing literature on this topic, which currently shows two main trends: first, reliable ecological inference from opportunistic data improves when a set of basic information (e.g. observer identifier and effort through checklists) is recorded as well, as is the case with *eBird* or *eButterfly* (Sullivan et al. 2014; Prudic et al., 2017). Even the best statistical methods cannot compensate for missing information (Johnston et al., 2017; Callaghan et al., 2019; Kelling et al., 2019). Second, models performed best when different data sources (e.g. citizen science and professionally collected data) were combined (Roy-Dufresne et al., 2019; Robinson et al., 2020) or integrated to maintain the strengths of each data collection approach (Fletcher et al., 2019; Isaac et al., 2020).

A combination of data from *active* and *passive monitoring* is already being used for updating species occurrences and presence maps (Kampen et al., 2013, 2014, 2016; Werner and Kampen, 2015) and, to some extent, for species distribution models (Kerkow et al., 2019). But beyond that, it appears that the potential of the opportunistic dataset is hardly exploited, especially with regard to modelling species distribution and habitats. The 'Mückenatlas' data collection could provide many new insights into mosquito ecology, distribution, and epidemiology when unleashing the whole potential with sophisticated statistical methods.

6.3 The 'Mückenatlas' provides confirmatory and novel evidence

The urban mosquito ecology study presented in Chapter 4 used a subset of the 'Mückenatlas' submissions that included only samples caught by citizens inside their homes. The study had two objectives: first, to explore differences in indoor species communities according to the level of urbanisation, and second, to test the applicability of opportunistic data collection as the only source of information to answer the research question, thereby confirming or providing novel knowledge on urban mosquito ecology.

With respect to the first objective, the study demonstrated that indoor mosquito communities differ along an urbanisation gradient. These differences are mainly due to a decrease in species richness and a simplification of biodiversity with increasing urbanisation. The effects of urbanisation on biodiversity are well-known for many insect groups including mosquitoes (Knop, 2015; Wilke, Beier and Benelli, 2019) and therefore attest the confirmatory potential of the opportunistic dataset in terms of the study's second objective.

However fitting these results to existing theories of urban ecology, such as the urban homogenisation of species (McKinney, 2006), the results must be interpreted with caution. A recent study by Planillo et al. (2021) comparing distribution models for nightingales in Berlin based on data from structured, semi-structured, and unstructured surveys highlighted the need for precise data to account for bias caused by citizen behaviour, especially in cities or other geographically limited spaces. Simply put, it is impossible to directly infer the occurrence or even the distribution of species from citizen observations without including sampling effort, a reasonable coverage of existing landscape structures, and information on species absences.

The same is true for the 'Mückenatlas', although measures were taken to indirectly account for the *observer skills:* to consider differences in trapping abilities or intentions of citizen scientists, submissions were defined by evidence of one species at one particular location, regardless of the number of specimens sent. Although most participants actually trap only one mosquito, some send up to hundreds of arthropods trapped with professional devices. In doing so, we followed approaches to assess observer skills from unstructured data by means of other variables (Horns, Adler and Şekercioğlu, 2018; Henckel et al., 2020) than specific information on sampling effort provided by the participants (see Kelling et al., 2015, for the original concept of accounting for observer skills).

With the second objective of this study it could be demonstrated that the opportunistic dataset leads to new insights into mosquito biology: never before has the indoor mosquito biome been investigated to this extent in Germany. The simple reason for this research gap is that such a large-scale study is not practical with conventional mosquito monitoring approaches. In fact, the study was only possible due to the behaviour of the participants to preferentially collect mosquitoes where they live, without this being actively pushed by the organising team. This process is already moving in the direction of a *democratisation of science*. It proves that some research questions are only feasible through the involvement of the public in scientific research or can even be conceived through this (Newman et al., 2012). Other studies showed, too, that the involvement of the public can result in generating novel research questions (Mathews et al., 2019), in unexpected findings (Eritja et al., 2019), in benefitting from indigenous knowledge (Mwangungulu et al., 2016), and in influencing environmental policy decisions (Bonney et al., 2016). The impact of citizen science on the temporal dimension is also unprecedented and opens up new research opportunities. For example, Callaghan et al. (2020) reported that within only 18 months, citizens detected 77 percent of the frog species in Australia that were gathered over 240 years by experts.

On the flipside, the flexible and unstructured survey design of the 'Mückenatlas' allows for little control of the data consisting of citizens' opportunistic observations. Highly unstructured citizen science programmes are characterised by rather broad scientific objectives and flexibility in statistical analysis, such as the exploration of patterns (Brown and Williams, 2019). Consequently, the degree of complexity of the project design and the scientific objectives should match in order to avoid that the unpredictable behaviour of the participants lead to the project goals not being achieved (Chase and Levine, 2016; Burgess et al., 2017). However, knowledge on opportunistically collected data is growing rapidly, and first frameworks on how to instruct participants to improve sampling over time and space in semi-structured and unstructured citizen science programmes are emerging (Callaghan et al., 2019).

In this study, certain properties of the dataset and a number of quite simple statistical methods already allowed for confirmation of findings and new insights into mosquito ecology. It demonstrates the stand-alone applicability of the opportunistic dataset for research and its inherent high information content, which, as already concluded in Chapter 3, has not yet been exploited.

6.4 Homemade bias? The role of the media in shaping the data

Media relations are important to raise awareness of citizen science projects and trigger participation, but despite this relevance only few studies have addressed this topic (e.g. Chu, Leonard and Stevenson, 2012; Robson et al., 2013; Hecker et al., 2014). The aim of the study presented in Chapter 5 was to gain knowledge of the interrelation between media coverage and the activation of citizens to participate in the 'Mückenatlas'. Insights into these associations might help future citizen science projects to plan more targeted media communication to attract participants. They are also an indicator of how topics, such as mosquito-borne diseases or the importance of mosquitoes in the ecosystem, are successfully communicated to the public, thus increasing acceptance of and attention to mosquito research via the 'Mückenatlas'.

The association between numbers of media reports and submissions is quite clear: when and where there is an increase of media coverage of the 'Mückenatlas', then and there increases participation. Positive temporal associations between communication campaigns and participation frequency have been confirmed for other citizen science projects (Robson et al. 2013; Curtis-Robles et al., 2015; Crall et al., 2017). The positive association on a spatial dimension, e.g. that locations of a submission are nearer to a location of a media report than would be expected by chance, has apparently not been explicitly described before. Only older studies exist that suspect extensive communication to cause clustering of observations due to uneven spatial media coverage (Eidson et al., 2001; Mostashari et al., 2003).

In Chapter 3, we suggested that the topicality of mosquitoes in the media could be a decisive driver of the annual variation in submission numbers. Our assumption is corroborated by this study: the number of media reports as well as submissions vary depending on releases by the German Press Agency (dpa). It is very likely, for example, that the Zika epidemic in South America prepared the ground for increased attention to mosquito issues (World Health Organization, 2016). A particularly resounding dpa-release on that topic presumably triggered a disproportionately high number of mosquito submissions and media reports in 2016. Initial studies in connection with the Covid-19 pandemic have also shown that an epidemiological event can strongly influence the behaviour of participants in citizen science projects, for example on temporal and spatial activity patterns (Crimmins et al., 2021; Gundelund and Skov, 2021; Kishimoto and Kobori, 2021).

Another factor for the uneven response to the particular dpa-release and following strong media echo could be the quality of the text. The study results indicated, that a specific call to action in the title (e.g. *Send us mosquitoes!*) already leads to increased submissions and seems to have a stronger impact on the willingness to participate than referring to the danger or nuisance of mosquitoes. If the media reports then meet with increased attention from both the media and the public, as could have been the case when the Zika epidemic was featured in the media, the number of submissions will reach a maximum by mutual reinforcement.

As hypothesised in Chapter 2, media reports might also be partly responsible for the taxonomic bias towards non-native mosquitoes by featuring corresponding pictures or video clips of the Asian tiger or Asian bush mosquitoes. Sumner, Law and Cini (2018) already indicated the influence of the media in people's opposing attitudes towards bees and wasps, and on the citizen science platform *iRecord*, the Asian hornet (*Vespa velutina*) was increasingly (and exclusively falsely) reported following increased media coverage in the United Kingdom (Roy et al., 2015).

The connection between public relations via media and the activation of participants may already fall under the topic of general knowledge as it has hardly been dealt with in the field of citizen science. Yet it has much greater relevance, especially for unstructured programmes, than previously assumed. The mass media, which the 'Mückenatlas' uses in a scattergun strategy to recruit participants, strongly influences what, when and where citizens participate. This causes additional uneven taxonomical, spatial and temporal coverage of submissions that is in the end induced by the communication strategy of the project team itself. Backed up by these strong findings, the media is probably a further – and sometimes even homemade – element in the extensive set of sources of bias in opportunistically collected data that has barely been described so far.

6.5 Conclusions

Purely quantitatively, the 'Mückenatlas' is a successful project. With more than 154,000 physical samples sent in over 28,000 submissions from more than 13,000 unique locations by June 2021, it has been continuously attracting citizens to catch mosquitoes for science. But the usefulness of the 'Mückenatlas' approach cannot be measured by submission numbers alone. The evaluations from different perspectives now provide knowledge on the actual contribution of the opportunistically collected data of the 'Mückenatlas' to mosquito research in Germany.

The *Method* work package results revealed the complementary nature of the *passive* and *active monitoring* approaches. It highlights the strengths of the citizen science approach in contributing data from previously unsampled areas, expanding sampling locations, and providing early and comprehensive detection of invasive species. The approach presented here can thus be recommended for formal mosquito monitoring programmes targeting a large area and long time periods, for sampling urban areas, or for tracking invasive species. Restrictions arise on the one hand from the socio-economic status of the country, because the costs for submissions are covered by the participants, and on the other hand from the research subject. Taxa that are easily recognisable, are negatively or positively connoted with human experiences, and have a relevance for human or animal health, have been proven suitable for citizen science projects (Goldstein et al., 2014; Porter et al., 2019; Lehtiniemi, Outinen and Puntila-Dodd, 2020). Therefore, citizen science can make a strong contribution by engaging communities, reducing costs, and obtaining accurate data, for instance in the context of integrated vector management as recommended by the World Health Organization (World Health Organization, 2012) or the management of alien invasive species as proposed by various decentralised sources (e.g. the Union for Conservation of Nature, 2021).

The unstructured and analogue 'Mückenatlas' approach may be less suitable for monitoring species whose identification needs to be trained, e.g. bumblebees (Roy et al., 2016). Furthermore, if left unchanged, the method would not be useful for projects involving local communities to study specific habitats or, as the ultimate programme goals, to achieve changes in attitudes and behaviour or to promote scientific literacy (see examples in Chandler et al., 2012, or Danielsen et al., 2014).

The citizen science project allows a form of *baseline monitoring* that hardly needs to be supplemented by a trap network. Hence, it gives the opportunity to carry out the working groups' *active monitoring* studies on mosquito ecology in a more targeted way, such as sampling river floodplains, restored wetlands, or remote areas. In this way, the funds provided are optimally used for all aspects of mosquito research in Germany.

According to Chapter 2, different participant activities create taxonomical distortions and uneven areal coverage. This was also evident in the studies of the *Data* work package: in the end, citizen scientists are mainly responsible for temporal and spatial biases through their (recording) behaviour. The sampling design of the 'Mückenatlas' project is unlikely to change towards a more structured approach to avoid bias in the first place. It neither makes sense for the project goals to involve the participants in the determination of mosquitoes, which is already complex for experts, nor to jeopardise the high participation rate by setting a time or place for catching mosquitoes. This implies data integration as the best solution to benefit from the strengths of the opportunistic dataset, while compensating for its weaknesses with other data sources (Fletcher et al., 2019; Isaac et al., 2020). The complementary nature of *passive* and *active monitoring* supports this assessment. In fact, a combination of 'Mückenatlas' and *active monitoring* data fed into a fuzzy model, which also accounted for the spatial bias in the citizen science data, significantly improved previous attempts to model the distribution of *Aedes japonicus* (Kerkow et al., 2020).

The necessary efforts to compensate for the biases are easier to accept when understanding the huge potential underlying the dataset as presented in Chapter 4. For example, it allowed to gain hitherto unknown insights such as into the mosquito indoor biome – a question that only came up and could be answered by including the public. Thus, an "army of citizen scientists" (Oberhauser and Prysby, 2008) does not only represent unpaid, exploited data gatherers (Riesch and Potter, 2014; Resnik, Elliott and Miller, 2015). Our example shows that even within a project focused on data collection, a promise of citizen science gradually becomes fulfilled: a transformation of how knowledge is produced and who produces it (Strasser et al., 2018). In this sense, the 'Mückenatlas' data collection scheme adds new perspectives and possibilities to mosquito research while reducing the distance between science and society.

The findings of the *Outreach* work package indicate that mass media have a major impact on the number of submissions to the 'Mückenatlas', both through the quantity and quality of media reports. Unexpectedly, quantity and quality of mass media reports may also be the cause of taxonomic, temporal and spatial biases. As a result, on the one hand, project organisers should use mass media wisely, as the consequential behaviour of potential participants might be influenced by style, illustration and contextualisation of the media reports. On the other hand, media can be very useful to guide the participants in a certain direction, e.g. to look out for specific species or to collect at undersampled sites.

The outreach activities of the 'Mückenatlas' thus have a double impact on mosquito research in Germany: they shape the opportunistic dataset and (should) additionally inform about mosquitoes and the need for research. For the latter, media work is assumed to raise awareness of the health and ecological relevance of mosquitoes, but so far there is no evidence other than the positive association between media attention towards mosquitoes, media coverage and submission numbers.

6.6 Future research

From a research perspective, the 'Mückenatlas' is a valuable component of national mosquito monitoring, but for the citizen science community it would also be important to learn more about the project organisation and the cost-effort ratio in comparison to *active monitoring*. In addition, *passive monitoring* was only evaluated quantitatively in the comparative study of Chapter 2. Qualitatively, the ratio of the different data sources that were actually used for further research and publication should be investigated as well.

Future studies on mosquitoes using the opportunistic data collection could benefit from its biases. In the context of climate warming and accelerated urbanisation, the overrepresentation of submissions from populated areas might be further useful. For the study in Chapter 4, all samples were combined into their respective genus, so the characteristic of a frequently submitted species could have strongly influenced the overall result. Repeating the analysis at species level could identify the individual taxa responsible for the trends towards a particular urbanisation category. It would also be interesting to select different large German cities to compare local mosquito communities. This would help to find out whether surrounding landscape structures, building types, or living environments influence the community composition. Epidemiological studies making use of citizen science data are also possible, and, in fact, are already being addressed (Wieland et al., 2021).

As the media dataset was re-purposed from marketing to research, many shortcomings in the data hindered a more qualitative approach to give specific recommendations on how to customise communication strategies. Experimental approaches with dpa- or press-releases of different wording would be one way to learn more about which messages work best to raise awareness of the citizen science project and to trigger participation.

Looking beyond the 'Mückenatlas', cross-national or continental studies involving citizen scientists could expand our knowledge of mosquito invasion processes and species responses to climate change and urbanisation on larger scales, but also provide more insights into the citizen scientists involved in these projects. For example, a bilateral project between the analogue 'Mückenatlas' and the app-based Spanish 'Mosquito Alert' is underway to identify differences in the participants' motivations, behaviour, and demographics between the projects. Since the morphological determination of mosquito species is difficult and thus represents a decisive cost, time and personnel investment, artificial intelligence will play a major role in the future of mosquito-related citizen science. While methods for image-based identification of mosquitoes are being developed (Park et al., 2020; Pataki et al., 2021), a new platform has been announced to automatically identify mosquito larvae and adults from citizen photo recordings, thereby combining citizen science and artificial intelligence for mosquito surveillance across the Americas (Woodrow Wilson International Center, 2021). However, since mosquito-borne diseases are in particular a burden for the African population, with, for example, 90 percent of yellow fever (Braack et al., 2018) and 94 percent of malaria (World Health Organization, 2021) cases worldwide, much more effort and resources should be put into supporting mosquito research and surveillance involving the public in these critical and underrepresented areas.

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I hereby certify that I have produced this thesis independently and that I have not used any sources and aids other than those listed.

Berlin, 2021