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PAPER

Mosquito Alert: Leveraging Citizen Science to Create a GBIF Mosquito Occurrence Dataset

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Abstract

Here we present the Mosquito Alert dataset, which includes occurrence records of adult mosquitoes. The records were collected through Mosquito Alert, a citizen science system for investigating and managing disease-carrying mosquitoes. Each record presented in the database is linked to a photograph submitted by a citizen scientist and validated by entomological experts to determine if it provides evidence of the presence of any of five targeted mosquito vectors of top concern in Europe (i.e. *Aedes albopictus, Aedes aegypti, Aedes japonicus, Aedes koreicus, Culex pipiens*). The temporal coverage of the database is from 2014 through 2021 and the spatial coverage is worldwide. Most of the records from 2014 to 2020 are from Spain, reflecting the fact that the project was funded by Spanish national and regional funding agencies, and since Autumn 2020 the dataset expanded across Europe, being most of the records from The Netherlands, Italy, and Hungary. The European expansion is made possible thanks to a human volunteering network of entomologists coordinated by the AIM-COST Action, and the development of technological scalability through the VEO project. Among many possible applications, Mosquito Alert helps to facilitate the development of citizen-based early warning systems for mosquito-borne disease risk. This dataset can be further re-used for modelling vector exposure risk or training machine-learning detection and classification routines on the linked images, to help experts in data validation and build up automated alert systems.

Classifications: Ecology; Taxonomy; Biodiversity.
Key words: Medical Entomology; Vectors; Crowdsourcing.

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Data Description

Background

Vector-borne diseases (VBDs) are infections caused by pathogens transmitted by carrier species (vectors), most of which are arthropods. VBDs are a major global health issue, with 80% of the world's population at risk of one or more of these diseases [1]. VBDs account for 17% of the global burden of communicable diseases with over 1 billion infections and over 700,000 deaths caused by VBDs annually [1]. Many of these diseases, once limited to tropical and subtropical zones, are now increasingly seen in temperate areas [1, 2].

Among VBDs, mosquito-borne diseases (MBDs) account for a large share of cases. In 2017 the World Health Organisation estimated over 347 million MBD cases and over 447,000 deaths caused by MBDs annually [1]. Of the 3,591 known species of mosquitoes (order Diptera; family Culicidae) [3], only a fraction are involved in disease transmission or cause considerable nuisance to human and animal populations. These include invasive species that are spreading throughout Europe due to globalisation and climate change [2, 4].

There are five mosquito vectors of primary concern in Europe, four *Aedes* invasive mosquitoes (AIMs) and the native *Culex pipiens* (northern house mosquito). The four AIMs established in Europe are *Ae. (Stegomyia) aegypti* (yellow fever mosquito), *Ae. (Stegomyia) albopictus* (Asian tiger mosquito), *Ae. (Hulecoetomyia) japonicus* (Asian bush mosquito) and *Ae. (Hulecoetomyia) koreicus* (korean bush mosquito) [5]. Their ability to spread into new territories, and their capacity to act as vectors of tropical viral diseases such as dengue, chikungunya, Zika, yellow fever and Japanese encephalitis, make AIMs key vectors of public health relevance [6]. Notably, *Ae. albopictus* has already caused outbreaks of exotic arboviruses in Europe, i.e. outbreaks of dengue in Croatia, France, Spain and Italy [7, 8, 9, 10], and two of chikungunya in Italy [11]. In Europe, *Culex pipiens* is considered the principal vector of West Nile virus (WNV) [12, 13] and Usutu virus [14]. Since 2010, the WNV epidemiological pattern in Europe has evolved, with an increasing incidence of human and horse cases after what began with a very low level of endemicity. Several WNV outbreaks have occurred during the last decades and there was a significant peak in incidence in 2018, with 1,503 cases in the European Union [13, 15, 16].

Given the absence of effective vaccine solutions for most MBDs [17], vector surveillance is critical and needs to be strengthened and coordinated on a global scale. Currently, no global surveillance system is in place to track the emergence and spread of MBDs [18, 19]. Increased mosquito surveillance is needed for timely detection of changes in abundances and species diversity, providing valuable knowledge to health authorities and enabling swift mosquito control responses and other public health interventions.

Obtaining field information with traditional mosquito surveillance tools is notoriously costly and time-consuming, and a major drawback of these tools is that they lack scalability. Costs can be significantly reduced by combining citizen science approaches with traditional ones for targeted surveillance [20, 21], and using big data spatial modelling techniques to compute risk maps of vector presence and abundance, human-vector interactions, and disease transmission zones at local or regional scales [22, 23]. Citizen science and the use of digital and networked technologies (Internet, mobile phones) have provided a new dimension to scientific research in the fields of vector ecology, eco-epidemiology, and public health [24, 25].

In the context of MBDs, a considerable amount of ongoing citizen science surveillance projects (29 projects operating in 16 countries all over the world, including some with wide geographic coverage) [26] have successfully involved public participation and provided data on mosquito populations. For future improvement, there is a need to continue engaging with stakeholders, researchers, public health agents, industry, and policymakers.

Context

Mosquito Alert is a citizen science system aimed at investigating and managing disease-carrying mosquitoes. It has been operational since 2014, with most participants initially located in Spain and participation expanding worldwide, particularly in Europe since 2020 [20, 27]. It uses mobile phones and the Internet to bring together citizens, scientists, and public health authorities to fight against MBDs. Mosquito Alert combines authoritative data with citizen science methodologies for data quality assessment and modelling, enabling large-scale estimates of mosquito population dynamics and the human-mosquito interactions through which MBDs are transmitted across a range of scales.

The data set presented here was collected through the Mosquito Alert mobile phone application. Citizen scientists provide geo-localized reports and images of targeted mosquito species, breeding sites and biting behaviour. Mosquito Alert also includes a module for sending samples to reference research labs in Europe that can be launched when and where considered necessary, allowing these labs to perform vector specialised identification and screening analyses. In addition, the app collects anonymous information on the geographic distribution of participants in order to correct for sampling effort biases [20]. The application also includes a participant scoring and a notification system that provides scientific and educational contents to participants. These features are expected to increase engagement and encourage frequent and extensive participation [28].

The five target species that citizen scientists can report are *Ae. albopictus*, *Ae. aegypti*, *Ae. japonicus*, *Ae. koreicus*, and *Cx. pipiens*. The targeted *Aedes* species are relatively easy to identify in photographs, whereas *Culex pipiens* can be difficult to distinguish from other *Culex* species. App tutorials and communication with citizen scientists are used to facilitate the identification and reporting of the targeted species. Adult mosquito reports containing photos are validated independently by three expert entomologists from the *Digital Entomological Network* in a web-based private platform, the digital *Entolab*. In addition to these species of interest, expert entomologists also identify other species of mosquitoes (not targeted) and even other insect groups. These identifications are also valuable from an educational perspective, as they help citizen scientists understand differences between targeted and non-targeted mosquitoes/insects. Since manual inspection of digital images is not a scalable option, the Mosquito Alert database of expert-validated images has been used to train a deep learning model to find *Ae. albopictus* [29] and the other target species (work in progress). This artificial intelligence system will not only be a helpful pre-selector for the expert validation process but also an automated classifier giving quick feedback to the app participants, which is expected to contribute to long-term motivation.

In this dataset we must differentiate two periods: the period 2014-2020 (August) and the period 2020 (September)-2021. During the period 2014-2020 the project was mainly focused in Spain, funded from various national sources (see section Funding), and therefore, most of the reports are from there. During this period the system was looking for two invasive species: *Ae. albopictus* and *Ae. aegypti*. This mosquito surveillance tool has so far yielded valuable results. It has served to monitor the spread of *Ae. albopictus* in Spain [30, 31] and to investigate mosquito species dispersal mechanisms [32]. It was also the source of the first-ever confirmed observation of *Ae. japonicus* in Spain and it has served as the basis for estimating the *Ae. japonicus* distribution in northern Spain [33, 34]. Mosquito Alert also provided the first record of *Ae. (Fredwardsius) vittatus* in northwestern Spain and it has contributed to mosquito biodiversity knowledge more broadly [35]. In addition to all this, Mosquito Alert provides direct links between researchers, public health authorities and the general public, serving as a valuable means for promoting public awareness and education about MBDs.

From September 2020 to 2021 the project increased the number of targeted mosquito species to the five listed above, and expanded across Europe with the support of European funding (AIM-COST OC-2017-1-22105, CA17108; VEO SC1-BHC-13-2019,874735). These projects have facilitated the required changes to increase the number of targeted species, scale the system at European level, and promote the development of a *Digital Entomological Network* of experts, boosting the dissemination of activities across Europe to promote data collection and direct interaction with citizen scientists in different countries. In 2020 and 2021, the digital citizen science surveillance through Mosquito Alert was carried out in combination with pan-European harmonised field entomological sampling (AIMSurv campaigns) under the framework of AIM-COST Action. Data outputs of these activities are presented in this special issue, being the results of citizen science activities part of the whole Mosquito Alert dataset.

Methods

Study extent

There are no limitations in terms of geographic areas from which citizen are allowed to participate, so data can be sent from all over the world. Nevertheless, as explained in the previous Section, Mosquito Alert's main coverage has been in Spain, with increasing coverage in Europe since 2020, mainly in The Netherlands, Italy, and Hungary (Figure 1). The temporal coverage of the dataset is from June 18, 2014 to September 20, 2021 and its temporal distribution is represented in figure 2.

Sampling

There is no pre-set sampling frequency: participants can send as much data as they like wherever and whenever they like or can. Data sampling may be more intense in some periods due to dissemination events (e.g. project appearances in TV, Science Fairs, etc.) but is also naturally modulated by mosquito seasonal prevalence and activity patterns.

Method steps

There are typically five steps to build an occurrence record:

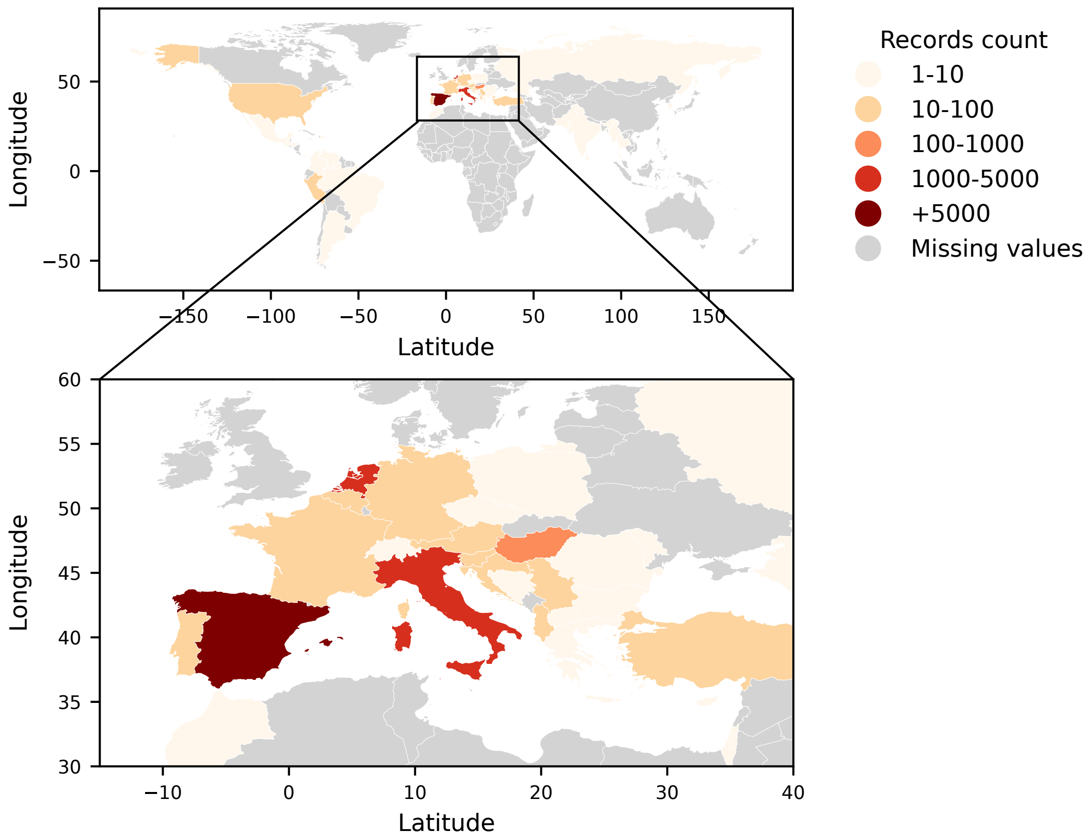

Figure 1. Mosquito Alert occurrence dataset spatial coverage from June 2014 to September 2021.

i. An anonymous citizen scientist observes an adult-mosquito (dead or alive).
ii. Within the Mosquito Alert smart-phone application, the citizen scientist answers a small questionnaire with taxonomic and environment-related questions, indicates the location of the observation, attaches one or more photographs (optional), and adds comments (optional).
iii. The report is reviewed by members of the Mosquito Alert team to remove anything that appears to be personally identifying information or inappropriate content.
iv. Each photograph attached to the report is evaluated independently by three entomologists, and each assigns a label to the report indicating their degree of certainty as to whether the photographs show the target species. A "not sure" label is used if an expert is not able to classify a report. A report is flagged if for any reason the report needs further discussion or should be temporarily left out from the public view. The final taxonomic classification comes from averaging the three expert validations (see section Data Validation and Quality Control).
v. The report is released into the public domain after the three entomologists' validation and reviewed by a senior entomologist who also checks flagged reports. As citizen scientists can try several pictures of the same specimen in one single report, one of the three experts has the responsibility to choose the final image released to the public domain (public map), which is the one published in the GBIF dataset. The selection criteria is to choose the mosquito image that best represents the observation, or the most valid for species determination.

Data Validation and Quality Control

The Digital Entomology Network is formed by a number of experts, including the so-called *National Supervisors*. At each European country participating through the projects AIM-COST and VEO, the *National Supervisors* serve as national level coordinators and supervisors. In addition, a senior entomologist *Super Expert* is in charge of the coordination of the whole validation flow and mechanics in the Mosquito Alert system. A manual for the expert validation system is distributed beforehand to the members of the network and published in the Mosquito Alert website [36] with specifications on the criteria for species determination.

The taxonomic determination of an observation results in two potential outputs indicating the degree of certainty: *confirmed*, when taxonomic features can be clearly seen in the picture/s and *probable*, when only some characteristic features can be observed. The final taxonomic determination and the relative degree of certainty is computed based on expert's validations in two steps:

i. *Selection of most voted category.* The selection for the most voted category is a simple majority selection. For example, assume the following three expert validation assessment: "Probably *Ae. albopictus* | Definitely *Ae. albopictus* | Probably *Ae. aegypti*". The most voted category is *Ae. albopictus* with two votes. Note that in this step, the "Probably" and "Definitely" qualifications given by each expert are ignored. If there is no majority (i.e, every expert chooses a different taxonomic category) the classification result is considered a "conflict" and the report is flagged and revised by the super-expert.
ii. *Certainty value selection.* The certainty labels of the most voted taxonomic category are mapped to integer values such that 1 corresponds to "Probably" and 2 to "Definitely". The final certainty assessment value is given by averaging the values and rounding them to the nearest integer value with a round half down strategy. For the above example, the most voted category is *Ae. albopictus* where two values are issued ("Probably" and "Definitely") that results in an average value of 1.5. Finally, after rounding the average to 1 the assessment

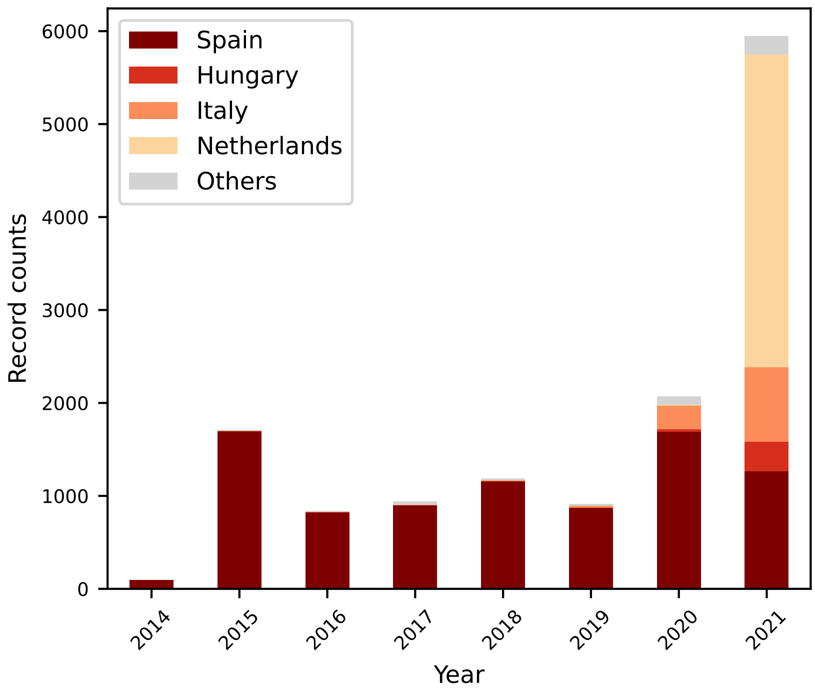

Figure 2. Mosquito Alert occurrence dataset temporal coverage.

gives a "Probable" *Ae. albopictus* occurrence. If the final result would be 2, the certainty degree of the occurrence would be labeled as "Confirmed". Note that rounding half down strategy implies a conservative approach in the certainty evaluation: if one of the expert expresses doubt, the overall value is decreased.

The validation procedure allows an expert to label a report with *not sure* in case of pictures with insufficient information. Those records are not included in the current dataset, since only confirmed or probable mosquito records are valid occurrences. For each record, the corresponding entomologist experts who reviewed it are cited by name or by a group label (e.g. institution, team name, etc.). The *Anonymous expert* label is assigned to experts who wish to remain anonymous.

Reuse Potential

This data set can reach many entomological (vector) surveillance and management objectives. First, due to its scalability and massive networking capability it can be used as an Early Warning System (EWS) for detection of invasive species across scales, from city to continental scales. At local scales this type of data can help optimise vector control, as citizen inform about nuisance and presence of mosquitoes at almost real time. Mosquito reduction campaigns, may combine top-down strategies of mosquito (larvae) control (undertaken by public health agencies) with bottom-up strategies promoting social action and behavioural change to reduce domestic and peri-domestic breeding sites' proliferation. Second, if combined with other data sources this data can be used to make risk assessments, like characterisation of critical areas and seasonal variability for disease risk transmission. It can also be used for data augmentation and calibration in mosquito distribution models of seasonal and inter-annual patterns as well as and spatial suitability maps. Third, the associated images contribute to train machine-learning models for image flow optimisation procedures in digital-based EWS and mosquito detection and classification.

Data Availability

The data set supporting the results of this article is hosted in the *GBIF-Spain* repository [37]. The associated multimedia dataset (mosquito pictures) is available on the *BioImage Archive* repository [38].

Declarations

List of abbreviations

AIMs: *Aedes* Invasive Mosquitoes; MBDs: Mosquito-borne diseases; VBDs: Vector-borne diseases; VEO: Versatile emerging infectious disease observatory; WNV: West Nile virus; EWS: Early warning systems

Ethical Approval

This data set involves human participation through a mobile phone app from which citizen scientists send text and image data. Participants must accept the Mosquito Alert *User Agreement* in order to use the app, and participation is anonymous.

Consent for publication

Consent to publish data is stipulated within the Mosquito Alert *User Agreement*, where a consent form is signed by the participant during registration.

Competing Interests

The author(s) declare that they have no competing interests.

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Author's Contributions

Živko Južnič-Zonta: Writing – original draft, Writing – review & editing, Data curation. **Isis Sanpera-Calbet:** Writing – original draft, Validation. **Roger Eritja:** Data curation, Validation. **John R. B. Palmer:** Conceptualization, Supervision, Funding acquisition, Software, Data curation, Writing – review & editing. **Agustí Escobar:** Software, Data curation. **Joan Garriga**: Data curation. **Aitana Oltra:** Conceptualization, Data curation, Project administration. **Alex Richter-Boix**: Project administration. **Francis Schaffner:** AIMSurv conceptualization, Resources. **Alessandra della Torre:** AIMSurv conceptualization, Funding acquisition, Resources. **Miguel Ángel Miranda:** AIMSurv conceptualization, Resources. **Luisa Barzon:** Resources. **Marion Koopmans:** VEO Conceptualization, Funding acquisition, Resources. **Frederic Bartumeus:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Mosquito Alert Digital Entomology Network:** Validation. **Mosquito Alert Community**: Investigation.

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Appendix

Table 1. Mosquito Alert Digital Entomology Network, list of collaborator names of authors.

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Table 2. Mosquito Alert Digital Entomology Network, list of collaborator affiliations.

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