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Involving citizen scientists in monitoring arthropod vectors of human and zoonotic diseases: The case of Mosquito Alert in Italy

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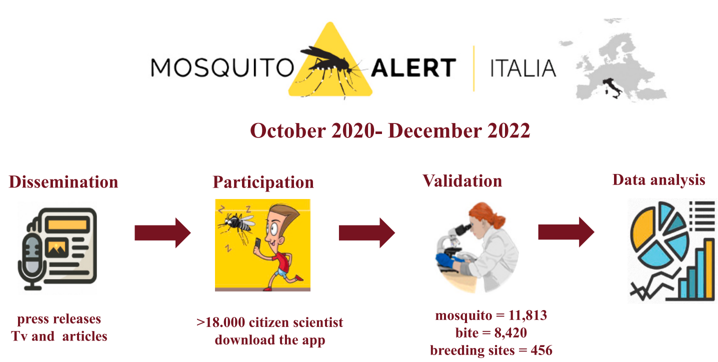
HIGHLIGHTS

- High citizen scientists recruitment via press releases detailing app goals and functionality
- Despite high app records, one-third of participants engaging sends at least one report
- Reporting peaks at registration (11.5 %), declines sharply, nears zero after ~50 days
- Participants' accuracy starts at 61 %, reaching 75 % in mosquito identification through app use

GRAPHICAL ABSTRACT



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ABSTRACT

Citizen science has been particularly effective in gathering reliable, timely, large-scale data on the presence and distributions of animal species, including mosquito vectors of human and zoonotic pathogens. This involves the participation of citizen scientists in research projects, with success strongly dependent on the capacity to disseminate project information and engage citizen scientists to contribute their time. Mosquito Alert is a citizen science that aids in the system surveillances of vector mosquitoes. It involves citizen scientists providing expert-validated photos of targeted mosquitoes, along with records of bites and breeding sites. Since 2020 the system

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App
Aedes invasive

has been disseminated throughout Europe. This article uses models to analyze the effect of promotion activities carried out by the Mosquito Alert ITALIA team from October 2020 to December 2022 on the number of citizen scientists recruited and engaged in the project, and their performance in mosquito identification. Results show a high level of citizen scientist recruitment ($N > 18.000$; 37 % of overall European participants). This was achieved mostly through articles generated by ad hoc press releases detailing the app's goals and functioning. Press releases were more effective when carried out at the beginning and end of the mosquito season and when mosquito's public health significance was emphasized. Despite the high number of records received ($N >$ 20.000), only 30 % of registered participants sent records, and the probability of a participant sending a record dropped off quickly over time after first registering. Among participants who contributed, ~50 % sent 1 record, ~30 % ≥3 and 4 % >10 records. Participants showed good capacity to identify mosquitoes and improve identification skills with app usage. The results will be valuable for anyone interested in evaluating citizen science, as participation and engagement are seldom quantitatively assessed. Our results are also useful for designing dissemination and education strategies in citizen science projects associated with arthropod vector monitoring.

1. Introduction

Citizen science involves the voluntary participation of anyone in the world in the production of scientific knowledge. Levels and types of engagement can vary, from gathering observations to processing and analyzing data, or even developing research questions and objectives, and drawing conclusions about outcomes. In recent years, technological innovations (e.g., smartphones, improved data connectivity, integrated GPS for real-time geolocation) have created many opportunities for easily recruiting "citizen scientists" leading to an explosion in the number of citizen science projects (Sousa et al., 2022). This has enabled the production of data at scales well beyond what professional researchers could accomplish on their own, while at the same time promoting education and raising public awareness on critical topics (e.g. environmental and public health protection), thus creating the potential for citizen scientists' direct involvement in decision-making processes and in the development of improved practices and policies.

One of the ways in which citizen science has been particularly effective is in gathering reliable, timely, large-scale data on the presence, ranges, and population distributions of plant and animal species, including mosquitoes. Citizen science mosquito projects have generally been motivated by concerns over both nuisance levels and public health, with many projects specifically targeting mosquitoes that are vectors of human and zoonotic diseases, such as dengue, West Nile and Zika viruses (see generally Sousa et al., 2022; Palmer et al., 2017). Several citizen science mosquito projects have been implemented at the country level in Europe in the last decade, making use of a variety of app interfaces designed to obtain specific kinds of data (from records of bites, to physical samples, to mosquito photos) and have produced interesting results. In Italy, ZanzaMapp has allowed estimates of mosquito abundance/nuisance based on citizen scientists' records of biting activity (Caputo et al., 2020). In Germany, Mückenatlas has allowed detection of changes in the country's mosquito fauna, based on samples collected from citizen scientists and mailed to specialists (Dekramanjian et al., 2023; Pernat et al., 2021). In the Netherlands, Muggenradar has illuminated the distribution of the biotypes of the night biting urban mosquito *Culex pipiens*, thanks to the physical collection of specimens by citizen scientists and their subsequent identification by professional scientists (Kampen et al., 2015). In Spain, Mosquito Alert has made it possible to trace the expansion of the invasive vector species *Aedes albopictus* (Delacour-Estrella et al., 2018) and to detect for the first time the presence of a second invasive species, *Aedes japonicus* (Eritja et al., 2019), based on georeferenced photos of adult mosquitoes sent by citizen scientists and identified via a web-based interface by a team of entomologists (Palmer et al., 2017).

Mosquito Alert was originally designed to receive photographic records of targeted adult mosquitoes and their breeding sites. In 2020, an updated version of the app added the possibility of reporting mosquito bites and was disseminated throughout Europe in 19 languages thanks to the *Aedes* Invasive Mosquito (AIM-COST) Action and Versatile Emerging Infectious Disease Observatory (VEO) project funded by the European Commission. As citizen scientists' reports streamed in from around Europe, Mosquito Alert became the first (and so far only) app to provide validated adult mosquito data at the continental level (Južnič-Zonta et al., 2022). The app is currently focused on mosquito species with the highest public health relevance in Europe and it is in the process of broadening its approach for implementation globally. The target species at the time of the research reported here were: i) *Aedes albopictus*, the Tiger Mosquito, which invaded Europe over 30 years ago and is now established in all Mediterranean and Balkan countries, further expanding northwards (Romi, 1995), and has already been responsible of dengue and chikungunya autochthonous outbreaks in Europe (ECDC, 2023a, 2023b); ii) *Aedes koreicus* and *Aedes japonicus*, two invasive species expanding in central Europe since 2011 (ECDC, 2023a, 2023b); iii) *Aedes aegypti*, the most widespread tropical species, not detected in Europe in the last decades, but reported in Cyprus in 2022 and in Spain's Canary Islands in 2023 (ECDC, 2023a, 2023b), raising great concern due to its very high efficiency as an arbovirus vector (Souza-Neto et al., 2019); iv) *Culex pipiens*, the "common house mosquito", endemic across Europe, where it is responsible for illnesses and deaths through autochthonous transmission of West Nile virus (Brugman et al., 2018). Unlike other mosquito monitoring apps, Mosquito Alert collects not only reports but also optional anonymous locations of participants. The app samples participants' locations (unless they opt out) approximately five times per day and masks these locations on a grid of 0.025 longitude and latitude (approximately 4 sq. km) before transmitting them from the phone. This masked location information is used to build up a spatial raster of the participants' inferred sampling effort, which can then be used as a control to reduce sampling bias in estimating human-mosquito interactions (Palmer et al., 2017).

Photographic mosquito records sent by citizen scientists are first identified by Mosquito Alert Entolab experts (whenever possible) and are later exploited for two major goals. The first goal is to facilitate nationwide year-round monitoring (unfeasible by traditional entomological tools) and to improve the capacity to detect colonization of new areas by invasive species, thus representing a continental-wide early warning system particularly relevant for early detection of *Ae. aegypti* to prevent its expansion in Europe. The second goal is to provide data on the five target species' presence and seasonality at national, regional, and local levels, to be ultimately exploited by local authorities for optimized mosquito control planning. This can also be achieved using photographic records of potential breeding sites and records of bites (which, however, cannot be validated as they are not associated with photos). The potential to gather data on mosquitoes and mosquito nuisance at local levels with limited costs compared to conventional monitoring is expected to create a virtuous cycle from citizen scientists to professional scientists and local administrations in charge of mosquito control and back. So far, the Mosquito Alert app has been relied on by public health authorities mostly in Spain; (Millet et al., 2017; Montalvo et al., 2021). Elsewhere, where there is less direct involvement by public authorities, the benefit for citizen scientists engaging in the project lies in: i) getting a feedback on the identification of their photographed specimens by Entolab experts; ii) accessing a map of all available validated records and model estimates via the Mosquito Alert website (www.mosquitoalert.com); iii) learning about the main mosquito vectors and means of preventing mosquito reproduction through the app and website contents. In addition, active participants are rewarded in the form of points based on the quantity and quality of the observations and on the frequency of participation and can rise in level and receive virtual trophies.

It is recognized that the success of a citizen science project with the ambition to be widely used relies on a structured communication campaign that plays a key role in both initial recruitment and in sustaining engagement (Chu et al., 2012). This should exploit different means of communication channels (Crall et al., 2017; Robson et al., 2013; Williams et al., 2017) and create original and captivating content (Chu et al., 2012; Pernat et al., 2022). Moreover, with specific reference to citizen science projects targeting arthropod vectors, it is also relevant to identify the optimal timing for dissemination related to the seasonality of the target species (Pernat et al., 2022). Presently, few studies have connected media communication campaigns with participation rates (Crall et al., 2017; Robson et al., 2013; van Vliet et al., 2014), and none of these have focused on mosquitoes.

The objectives of this paper are to understand which promotion activities were most successful, not only in recruiting citizen scientists in the Mosquito Alert project but also in engaging them to send records in a sustained way over time. In addition, we analyze the overall sampling effort and citizen scientists' performance in identifying the photographed mosquito species. The analytical approaches used are expected to be of interest to anybody willing to assess citizen scientists' participation and engagement in a project (which are rarely assessed), while the results obtained will be instrumental to improving dissemination strategies in the field of citizen science associated with arthropod vector monitoring.

2. Materials and methods

2.1. Mosquito alert app

Mosquito Alert is an open source smartphone application freely available for Android and iOS (currently version 32) on Google Play and the Apple Store, as well as on the official project websites (www.mosquitoalert.com; www.mosquitoalertitalia.it) and GitHub (https://github.com/Mosquito-Alert/Mosquito-Alert-Mobile-App). Through the app, participants can submit the following georeferenced reports: 1) photographic reports of adult mosquito specimens ("report mosquito" in the app); 2) reports of mosquito bites ("report bite"), 3) photographic reports of larval breeding sites ("report breeding site"). Upon first accessing the app, participants are provided with information about the app and the data they may share through it and they are prompted to provide consent in order to participate. The shared data can include anonymous background location information used in estimating "sampling effort", as described below. To protect participants' privacy, the background locations are masked on a grid of 0.025 longitude and latitude (approx. 4 sq. km) prior to being transmitted from the phone. In addition, the app associates the masked background locations from each participant with a random UUID that is different from the UUID associated with participants' reports.

2.2. Mosquito Alert ITALIA data

Immediately after the release of the updated Mosquito Alert app in Europe in October 2020, a Mosquito Alert ITALIA team was created through a memorandum of understanding between the Department of Public Health of Sapienza University, as the coordinating institution, and the National Institute of Health (ISS), the zooprophylactic Institute of Veneto regions (IZSVe) and the Museum of Natural History of Trento (MUSE). The coordinating and collaborating institutions actively contributed to the promotion of the app through press releases, interviews, university and secondary school student projects and participation in local events (see below). The estimated costs associated with the production of material for the app promotion were those associated with the Mosquito Alert ITALIA webpage creation and management, the production of two short video tutorials in Italian for the app (https://www.youtube.com/watch?v=0fwRzChUfcE), and the project (https://www.youtube.com/watch?v=d_J_pJNWko0), and printed leaflets and materials for local dissemination events. From 6 October 2020 to 31 December 2022, the Mosquito Alert ITALIA team obtained the highest number of registered participants and the highest number of records out of all European countries, including Spain.

Data were extracted from four Mosquito Alert databases for the period from 6 October 2020 to 31 December 2022, and were merged with a spatial grid covering the Italian National territory with cells size of 2.5 × 2.5 km, spatially joined with Mosquito Alert sampling cells, derived from records coordinates rounding (note that there is a temporal gap in this data from 16 to 26 July 2022, due to a technical issue that blocked reporting possibility). Each grid cell was joined with spatially explicit geographic information derived from thematic maps and assigned to three of the Biogeographical Regions of Europe defined by Cervellini et al. (2020). The Alpine biogeographic region includes mountainous areas in norther Italy, with low productivity and high levels of endemism. The Continental biogeographic region in the northern-central part of the country features a continental climate with warm summers and cold winters, large rivers, high soil fertility, and extensive crop production and animal farming. It includes large urban areas with dense infrastructure, leading to significant habitat fragmentation. The Mediterranean biogeographic region in the southern part of Italy has a warm climate with hot summers and mild winters, increasing arid and desert conditions, and low humus soils with high erosion risk. Fractional population size of municipalities (source: http://dati.istat.it) residing in each cell was calculated, using a weighted spatial overlapping approach. Four databases were generated: 1- ParticipantDB, i.e. "Italian participant masked location" database; 2- finalDB, i.e. "Italian raw record" database; finalDB, i.e. "Italian final record" database; 4 newsDB, i.e. the "Italian Mosquito Alert news" database including a description of the dissemination events and activities carried out in the study period (Sup Mat, File S1).

ParticipantDB and RawDB were provided through a secure mechanism upon request to the Mosquito Alert Spanish team, as these are not part of the project's publicly available datasets.

2.3. Evaluation of participants' recruitment and engagement

We computed several parameters to characterise participants' engagement and app usage: i) count, temporal dynamics and spread of registered participants in ParticipantDB; ii) number of records, spatial and temporal distances among records and mean number of raw records for each participant using rawDB; iii) number and characteristics of validated records, and agreement on the identification of the mosquito species by participant and entomological expert using finalDB.

We also computed the incidence of registered participants in each municipality compared to its population using PartecipationDB. All descriptive analyses were computed for each year (2020, 2021, and 2022) separately and we tested for differences in the observed data of 2021 and 2022 with Fisher's and Chi-squared tests. The mean distance among records of each participant was obtained by calculating for each participant the Euclidean distance matrices (EDM) of squared distances among records. In addition, the time among records of single participants was calculated as the days elapsed between each participant's records.

2.4. Promoting participant recruitment and engagement

We analysed the relationship between participant recruitment and engagement and the typology of communication events (i.e. TV/radio, articles and face-to-face) using ParticipantDB, RawDB and newsDB. Due to the short time window in 2020, we considered only those events carried out in 2021 and 2022. The models for national events (TV/radio and newspaper) were carried out for each Italy province (106 provinces) while the model for local events (face-to-face and newspaper) was carried out only for the 22 provinces where face-to-face meetings were done.

We framed our analysis as a pre-post design using a Generalized Linear Mixed Model approach (GLMM). We considered as a response variable either the total number of new participants or the total number of records within two time periods of equal duration before and after each communication event. We considered a time window of two-days (considering the day of the event in the post-time window) and carried out a sensitivity analysis exploring different durations. We assumed the response variable to follow a Negative Binomial distribution after checking for overdispersion.

We developed three GLMMs:

In MODEL-1 we assessed which national event (TV/radio or national news) had a greater impact on participant recruitment and participant engagement. We include as independent variables a qualitative variable identifying the time window before or after the event (i.e. pre/post), the event typology (i.e. TV/radio or newspaper), and their interaction (pre/post*typology);

In MODEL-2 we assessed in which period (early, central, and late mosquito season) the publication of articles in the news had a greater impact on participant recruitment and participant engagement. We include as independent variables a qualitative variable identifying the time window pre or post the event (i.e. pre/post), seasonality (i.e. early/high/late), and their interaction (pre/post* seasonality). We defined May–June as the early season, July–August as the central season, and September–October as the late season. As a sensitivity analysis, MODEL-2 was fitted with and without considering any article published within a week after a press release from the Mosquito Alert ITALIA team to assess the impact of the direct communication effort.

In MODEL-3 we assessed which local events (face-to-face or local newspaper) had a greater impact on participant recruitment and engagement. We used the same statistical structure described in MODEL-1 considering face-to-face and local newspaper events rather than TV/radio and national newspapers.

In all models, we considered Italian provinces as a random effect term and included the human population density and the age structure at the province level as covariates. The data for human population density and age structure was obtained from ISTAT (Italian National Institute of Statistics) using the most recently available census and population survey (2021; https://www.istat.it/it/archivio/285267).

2.5. Probability of sending at least one record

The individual probability of sending a record (π) was estimated as a function of the time elapsed since the app download and the last activity (quantitative variable: hereinafter “participation time”). We considered participants enrolled from 2021 to 2022 and included the ID of the participant as a random effect to account for individual variability. We used a Generalized Additive Mixed Model (MODEL-4) considering a daily binary outcome variable, identifying as 1 the days when the participant sent a record and 0 otherwise. The participation time was calculated from 1/1/2021 to 31/12/2022 and was included as a smoothing function to model the non-linear temporal effect of π. We applied the resampling technique used in Palmer et al. (2017) to account for data imbalance (Fig. S1). Finally, π was modelled for 2021 and 2022 separately to compare the two years, following the same statistical approach explained above (File S2). For this analysis, we used ParticipantDB and RawDB.

2.6. Mosquito alert sampling effort

We computed an estimate for Italy of the Mosquito Alert sampling effort following Palmer et al. (2017). Sampling effort (hereafter SE) in each sampling cell was defined as the sum of the individual probabilities of sending a record of each participant active in the sampling cell in a previous two-week period. Intuitively, the value of SE should correspond to the expected number of participants who would send at least one record through the app in the two-week period under the assumption that the probability of sending a record for each participant depends only on their participation time. To compute this analysis, we used ParticipantDB and the predicted probability of sending a record as estimated beforehand (see Probability of sending at least one record section). Finally, to model the dynamics of SE as a function of the two-week period we fit Generalized Additive Models (MODEL-5) assuming SE was Gamma distributed. The two-week period was included as a smoothing function (quadratic spline) to model the non-linear temporal effect of SE.

2.7. Citizen scientists’ performance in mosquito identification

The performance of Italian Mosquito Alert participants in identifying mosquito species was assessed by Generalized Additive Mixed Models (MODEL-6) of the agreement between classifications provided by the participants (either “*Aedes* invasive”, or “*Culex* spp.”) to those provided by Entolab experts (either “*Aedes* invasive”, or “*Culex* spp”, or “other species”) as a function of participation time (days between participant’s registration and record recording) using the 2021–2022 Mosquito Alert data. We assumed that the response variable follows a Bernoulli distribution, coding it as 1 if the species classification between the participant and expert team agrees or when the participant answered, “I don’t know” and the expert team classified the record as “Other species”. We coded the variable as 0 in the following circumstances: i) the participant answered, “I don’t know” in the questionnaire and the expert team classified the record as invasive *Aedes* or *Culex* sp., ii) the participant answered “invasive *Aedes*” and the expert team classified the record as *Culex* sp. (vice versa for *Culex* sp.); iv) the participant answered “invasive *Aedes*” or “*Culex* sp.” and the expert team classified the record as “Other species”. We excluded the records identified by experts as “not sure” and “unclassified” (see Table S1, for further details on expert classification labels). The participation time of each participant was included as a smoothing function (2-degree) and the unique identifier of each participant as a random intercept term. Due to a few participants having a high value of participation time, we dropped the highest 5 % of the participation times. For this analysis, we used finalDB.

All analyses were conducted using the statistical software R, version 4.2.3 (R Core Team, 2020).

3. Results

Results on the participation and performance of citizen scientists in the Mosquito Alert ITALIA project are provided below. Unless otherwise specified, the results refer to data from Italy in the period between the first press release of the Mosquito Alert app in Italy (6 October 2020) to the end of 2022 and are discussed comparing 2021 versus 2022 data.

3.1. Citizen scientists registered with Mosquito Alert in Italy

A total of 18,291 (4 % in 2020, 46 % in 2021 and 50 % in 2022; Table 1; Fig. 1) citizen scientists downloaded the Mosquito Alert app, consented to the monitoring of their sampling effort (i.e. to the collection of anonymous, masked background locations from their device; hereafter referred to as registered participants), and were recorded as having been located within Italy at some point during the study period.

Table 1
Use and promotion of Mosquito Alert app in Italy from 6 October to 31 December 2022.

Data	Oct-Dec 2020	2021	2022	p-Value
Number of new users (database1)	664	8574	9053	<0.001
January–March	–	1.4 %	2.3 %	
April–June	–	23 %	46 %	
July–September	–	28 %	39 %	
October–December	100 %	47 %	12 %	
Alpine	7.5 %	5.3 %	5.4 %	
Continental	38 %	48 %	45 %	
Mediterranean	55 %	47 %	49 %	
% users sending ≥1 raw report	36 %	34 %	34 %	>0.05
Number of raw reports (database2)	628	8631	11,467	<0.001
Mean distance among raw reports by single users (km)	8.1	14.2	15.4	>0.05
Mean time among raw reports by single users (days)	8	11	11	0.6
Mean number of raw reports for each user	2.6	3.0	3.8	<0.001
Raw Report Location choice				<0.001
Provided by the app ($N = 16.488$)	78 %	82 %	78 %	
Selected manually ($N = 4.328$)	22 %	18 %	22 %	
Dissemination event (database4)	$N = 6$	N = 26	$N = 104$	<0.001

	Local (2)	Nat (4)	Local (19)	Nat (7)	Local (63)	Nat (41)
Face-to-face	100 %	0	47 %	0	28 %	0
Newspaper	0	100 %	53 %	72 %	71 %	92 %
TV and radio	0	0	0	28 %	1 %	8 %

Registered participants were located in all Italian provinces (106) and in 43 % of municipalities (3405/7904), and were distributed 50 %, 44 % and 6 % in Mediterranean, Continental and Alpine biogeographic regions, respectively. The number of registered participants per 100,000 inhabitants in the 10 municipalities with >100 registered participants ranged from 29 in Naples to 121 in Trento (Table S2).

3.2. Records by registered Mosquito Alert participants in Italy

About a third of registered participants (6180) sent at least one record, for a total of 20,726 records (Table 1). Among participants who sent at least one record, 48 % sent one record only; 22.3 %, two records; 25.3 % from 3 to 10 records; and 4.4 % >10 records for a mean of ~3 records/participant. The mean distance between records by single participants was ~15 km and the mean number of days between records by single participants was ~20 days, with no differences between years. About 80 % of records included locations recorded by the app.

3.3. Photographic records of adult mosquitoes

More than 70 % of the adult mosquito reports received in Italy ($N = 314/461$ in 2020, $N = 3345/5125$ in 2021, $N = 4542/6128$ in 2022; Table 2) included at least one photo (76 % had only one photo; 18 % had 2; 6 % had >2). Of the reports including at least one photo ($N = 8201$) >63 % were confirmed as mosquito records by national Entolab expert teams. Identification of one of the five species was obtained by Digital Entolab experts for 4942 records (2020 = 206; 2021 = 1942; 2022 = 2794), corresponding to an overall 95.4 % of records identified. Most mosquito photos were identified either as *Ae. albopictus* (2020 = 27 %; 2021 = 53 %; 2022 = 69 %) or as *Culex* spp. (2020 = 73 %; 2021 = 47 %; 2022 = 30 %) (Table 2). A total of 4 and 17 records were identified as *Ae. japonicus* and *Ae. koreicus*, respectively, and discrimination between the two species was not achieved for an additional seven records. No records

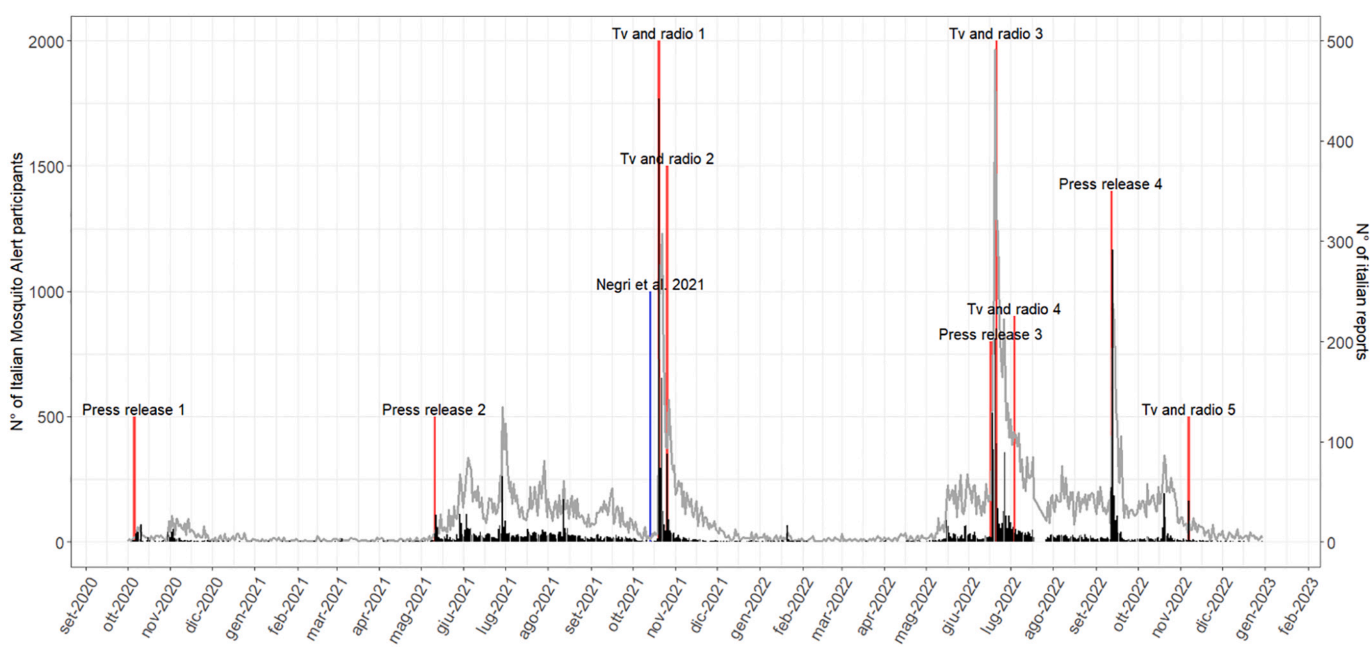

Fig. 1. Numbers of univocal registered Mosquito Alert participants (one per participant tracking IDs; in black) and number of reports (in grey) from the release of the app in Italy in October 2020 to end of 2022. Red vertical lines refer to major dissemination events, as follows. Press Release 1 (PR1; 6/10/2023): Che fine fanno le zanzare d' inverno? Un' app può aiutare a scoprirlo. PR2 (11/05/2021): Lotta alle zanzare: approda in Italia Mosquito Alert, l'app che permette ai cittadini di contribuire con un click. PR3 (17/06/2022): Estate, tornano le zanzare: i cittadini al fianco dei ricercatori nel tracciamento con l'app Mosquito Alert. PR4 (12/09/2022): Zanzare che trasmettono West Nile e altri virus: con Mosquito Alert è possibile tracciarle. TV/Radio interview 1 (TV/R1; 20/10/2021): Dalla Corea la zanzara che non teme il freddo. TV/R2 (26/10/2021): Scienza. Invasione di zanzare aliene: il progetto dell'Università La Sapienza in tema; TV/R3 (21/06/2022): Tg Leonardo; TV/R4 (04/07/2022): Geolocalizza le zanzare - Telescopio cittadino, TV/R5 (07/11/2022): Noi tra gli insetti - Geo & Geo. Blue vertical line = Scientific paper on the spread of *Aedes koreicus* in the Lombardy region (Negri et al., 2021;14/10/2021).

Table 2
Mosquito Alert "reports of mosquito" from Italy from October 6th 2020 to December 31st 2022 (final DB). FinalDB includes a subset of rawDB records, i.e. all "Mosquito" records (with and without annexed photo), except for those with incorrect coordinates, accounting for lack of match between N in this table and N in Table 1. [a] = all records sent by participants under the "Report mosquito" in the app; [b] = all records identified as Culicidae. [c] = all records identified as Insect different from Culicidae. [d] = all records labelled as "Not sure" (see Table S1) and records in "Other species" not labelled by Spanish Mosquito Alert team· *P*-values refer to comparisons between 2021 and 2022. * = Wilcoxon rank, Fisher's and Pearson's Chi-squared tests as appropriate.

Data	Oct-Dec 2020	2021	2022	p-Value*
Numbers of validated Mosquito Alert reports	$N = 625$	$N = 8581$	$N = 11{,}483$	<0.001
"Mosquito" (with or without photo)[a]	75 %	60 %	54 %	
"Bite"	24 %	38 %	44 %	
"Breeding site"	1 %	2.5 %	2.1 %	
"Mosquito" reports with photo assessed by Entolab	314	3345	4542	<0.001
Mosquito ($N = 5175$)[b]	67.8 %	60.4 %	64,70 %	
Other insects ($N = 289$) [c]	11.8 %	5.3 %	1,70 %	
Not identifiable[d]	20.4 %	34.3 %	33.6 %	
Mosquito Alert target species identified	$N = 206$	$N = 1942$	$N = 2794$	<0.001
Aedes albopictus	27 %	53 %	69 %	
Aedes japonicus	0	0.1 %	≪0.1 %	
Aedes koreicus	0	0.2 %	0.5 %	
Japonicus/koreicus	0	0.1 %	0.2 %	
Culex spp.	73 %	47 %	30 %	

of *Ae. aegypti* were identified. In addition, 233 mosquitoes belonging to *Aedes* (153), *Anopheles* (17), *Coquillettidia* (1), *Culiseta* (57), *Culex* (5) genera were identified.

In a subset of 430 photos screened to identify mosquito gender, 95.6 % were identified as females. Of these, 28 % were classified as blood-fed, 60 % were classified as either unfed or gravid and in 12 % of the photos the abdomen was either not visible or not identifiable.

3.4. Impact of dissemination on citizen scientists' recruitment and engagement

During the time-frame considered, a total of four press-releases were launched in Italy leading to 30 online articles in the two following days (Fig. 1; Table S3). The Mosquito Alert app was also quoted in 51 online articles not directly linked to press releases and five TV/Radio interviews of Mosquito Alert Italia members. The following results refer to the increase and average number of new participants and reports per province comparing the two days before with the two days after the communication events, controlling for human population density and age structure and including random intercepts for province to capture remaining province-level variation in new participants and reports not explained by the communication events.

The effect of overall online articles and TV/Radio interviews (Table S4) on participant recruitment and engagement was analysed by GLMMs. MODEL-1 shows a significantly higher increase in both new registered participants and reports after online articles (new participants: 5.5-folds, 95%CI 5.3–5.6; records 3.7-folds, 95 % CI 3.5–3.9) than after TV/radio interviews (3.1-folds, 95%CI 2.9–3.3; 2-folds, 95 % CI 2.6–2.6; *p*-value <0.0001, Table S5). However, on average, TV/radio interviews led to a higher number of registered participants (1.9; 95 % CI 1.6–2.3) and reports (0.9; 95 % CI 0.7–1.1) than article publications (new participant = 0.8; 95%CI 0.6–0.9; reports = 0.5; 95%CI 0.4–0.6).

The impact of press releases on participant recruitment (registered participants) and engagement was analysed by MODEL-2 in relation to mosquito seasonality. Overall, a significant increase in both new participants and reports was found in the early season (May–June) (new participants: 6.5-folds, 95%CI 6.3–6.6, records: 2.9-folds, 95%CI 2.8–3.1) and late season (September–October) (new participants: 6.0-folds, 95%CI 5.8–6.2, records: 2.6-folds, 95% CI 2.3–2.8), with an average of 0.9 (95 % CI 0.8–1.0) and 1.0 (95 % CI 0.9–1.2) new participants and 0.6 (95 % CI 0.5–0.7) and 0.5 (95 % CI 0.4–0.7) reports, respectively (Table S6). When articles published in the week after the press releases were not included in the analysis, results show a significant increase in new participants only in the early season (new participants: 3.3-folds, 95%CI 3.1–3.5), with an average of 0.5 (95%CI 0.4–0.6) new participants (Table S7).

In addition, the Mosquito Alert Italia team carried out 27 face-to-face local promotional events (Tables 1; S8), leading to a 2.6-fold (95%CI 1.4–4.6) and 2.1-fold (95%CI 1.4–3.3) increase in the number of new participants and records in the province where the event was carried out (MODEL-3, Table S9). A similar increase is also found after articles publications in the same provinces (participants: 2.6-fold, 95%CI 2.1–3.3; reports: 1.5-fold, 95 % CI0.6–3.9; *p*-value >0.05; Table S9).

The sensitivity analysis reveals that results are consistent with respect to the span of the considered time window, i.e., 5 days versus 2 days pre/post event (See Sensitivity analysis section in Supplementary materials).

3.5. Probability of sending at least one record

Results - obtained by pooling 2021 and 2022 data, as no statistical difference was found between the two years in the probability of sending one record (Table S10, Fig. S2) – clearly reveal that the probability of reporting is highest on the day of registration (11.5 %, 95 % CI 7.7 %–16.4 %), decreases with participation time and approaches zero after ~50 days (Fig. 2, Table S11).

3.6. Sampling effort

The sampling effort for two-week periods during 2021–2022 was modelled by MODEL-5 as a function of participation time as well as intrinsic participant motivation (modelled as random intercepts).

Overall, the mean sampling effort of all sampling cells with at least one participant ($N = 9945$, i.e., 18 % of total sampling cells in Italy) was 0.181 (95 % CI 0.177–0.182). The maximum number of cells with non-zero sampling effort was recorded during the first two weeks of July (39 %, $N = 3866$ of sampled cells) (Fig. S3).

A non-linear relationship was estimated between the sampling effort and two-week period over the year (MODEL-5, TableS12) with higher

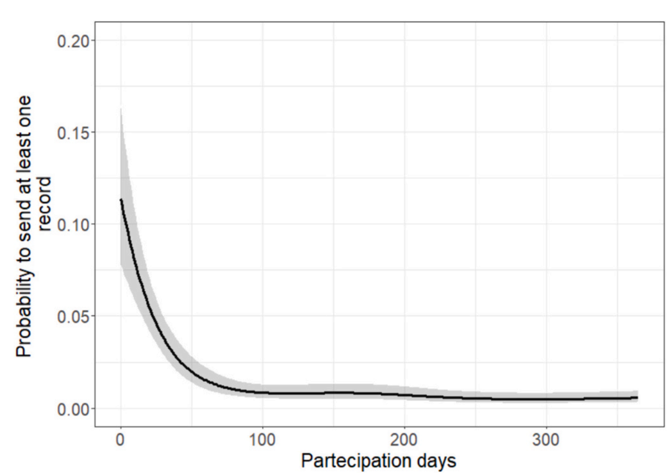

Fig. 2. Probability of a participant registered in Mosquito Alert app to send at least one record in Italy in 2021–2022 as a function of participation days. Continuous lines: predictions by MODEL-4, dashed area = 95 % of confidence intervals. Due to graphical convenience, we cut off at 365 days of "participation time" in order to have a one-year probability of sending at least one record of participants.

predicted values in the first two weeks of July (0.232, 95 % CI 0.226–0.238) (Fig. S4). In these weeks, the highest sampling effort was recorded in the main metropolitan areas (North; Milan, and Venice; Center: Rome; South: Naples) and along the coast (Fig. 3).

3.7. Participant performance in mosquito identification

Among the 7887 mosquito photographic records sent (Table 2), 66 % ($N = 5217$) included citizen scientists' identification of the specimen as either "Invasive *Aedes*" or "*Culex* sp.". By comparing these identifications with those later provided by Entolab experts, we assess Mosquito Alert participants' ability to discriminate between the two categories based on morphological characteristics. Overall, 86 % of citizen scientists' identifications were confirmed by experts. As shown in Table S13, out of 2457 records identified by citizen scientists as "Invasive *Aedes*", 94 % (95 % CI 93–95 %) were confirmed as such by experts, while 2 % and 4 % were identified as "*Culex* sp." and as "other insects", respectively. Out of 1715 records identified by citizen scientists as "*Culex* sp.", 74 % (95 % CI 72–77 %) were confirmed by experts, while 6 % and 20 % were identified as "Invasive *Aedes*" and as "other insects", respectively.

The assessment of the relationship between participant performance in mosquito identification and participation time (MODEL-6) shows a significant increase from 61 % accuracy (95%CI 59 %–64 %) at the beginning of app use to 75 % (95 %, CI 62 %–84 %) after 300 days (Table S14, Fig. S5).

4. Discussion

The overarching goal of this study was to provide suggestions useful for the successful promotion of citizen science projects on arthropod vector monitoring based on the modelling of data from the implementation of Mosquito Alert ITALIA project since its launch in October 2020 through the end of 2022.

4.1. Citizen scientists' recruitment

Despite the low-cost dissemination campaign and its design and implementation by non-professional communicators (i.e. members of the Mosquito Alert ITALIA team), the promotion of the app was successful in raising citizen scientists' interest in Italy and in recruiting them in the project. This is testified by the fact that ~37 % of the overall recruited participants in Europe during the study period ($N = 46{,}427$) downloaded the Italian version of the app. Recruited participants were distributed in 43 % of the 7904 Italian municipalities across all 106 provinces. Up to 121 new participants/100.000 municipality inhabitants were reached.

Results of the impact of major dissemination activities at the national level on participant recruitment (GLMM adjusting for human population density, age structure and Italian provinces as confounding effects), show that: 1) TV interviews generated an average of ~2 new participants/province in the two days following the interview (overall mean of >200 new participants per event in the 106 Italian Provinces) and doubled the number of new participants compared to online articles, likely due to the larger TV/Radio audience; 2) online articles mentioning the Mosquito Alert app/project were more successful in generating participant recruitment when published either during the early or late mosquito season as opposed to the middle season; 3) most of the new participants were recruited between April and September, i.e. either when mosquitoes start to bite and at the peak of the nuisance season in Italy (Manica et al., 2016; Montarsi et al., 2015). September 2022 press release was the most successful one (compared to those in October 2020, May 2021, and June 2022) in terms of generating article publications and recruitment of new participants, leading to a 55-fold increase of the latter within two days (versus no more than a 13-fold increase in the comparison periods). This may be due to the high mosquito nuisance and/or to the combination in the title of the words "West Nile" and "Mosquito Alert", stressing mosquito public health relevance. Interestingly, however, the highest peak of recruitment (a 113-fold increase in new participants) was not observed after a press release but two days after an interview of a member of the Mosquito Alert ITALIA team on national TV in October 2021(https://mediasetinfinity.mediaset.it/video/tg5/dalla-corea-la-zanzara-che-non-teme-il_freddo_F310638601170D07), following the large media coverage of a scientific publication reporting the spread of *Ae. koreicus* in northern Italy (Negri et al., 2021).

The above results are consistent with those from a recent study by Dekramanjian et al. (2023) suggesting that Mosquito Alert participants are largely driven by their antipathy of mosquitoes or by public health

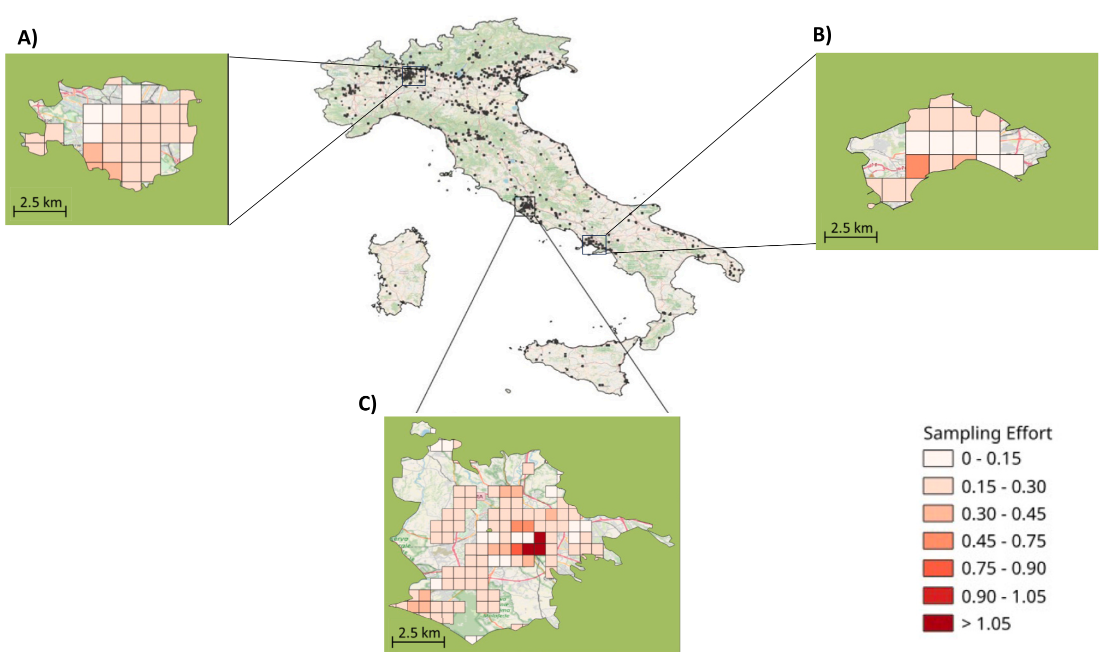

Fig. 3. Observed sampling effort by Mosquito Alert in the first two weeks of July (2021 + 2022) in Italy, Zooms = Observed sampling efforts in each sampled cell in Milan (A), Naples (B) and Rome (C).

concerns and may be more interested in supporting mosquito control than in the science behind the project. Overall, this implies that emphasizing the potential of digital tools to help reduce mosquito populations and contribute to an early warning system for the introduction and spread of vector species is a more successful communication strategy than relying on citizen scientists' curiosity about mosquitoes and willingness to support scientific progress. In addition, associating health-related issues with citizen science has been previously shown to increase journalist's interest (van Vliet et al., 2014), and this was confirmed here by the higher number of articles generated by the September 2022 press release ($N = 17$) compared to the other ones ($N \leq 7$).

These observations are also in line with results by (Pernat et al., 2022), who analysed the submission of physical mosquito specimens within the 'Muckenatlas' citizen science project in Germany. They found that media coverage of the 2015–2016 Zika epidemics in the Americas paved the way for greater attention to the relevance of mosquitoes for public health in Germany, resulting in higher citizen participation. Results showed that media reports and sample submissions track the seasonality of mosquito occurrence, suggesting that citizen engagement reflects the phenology of the study object, as has been shown in other citizen science projects for monitoring biodiversity (Curtis-Robles et al., 2015; van Vliet et al., 2014).

Local face-to-face dissemination activities (e.g. meetings in the primary school, university, and fairs) targeting specific audiences are shown to have the potential to attract as many new registered participants as major national dissemination activities, although at the province level rather than at the national one. Indeed, these in-person events make it possible to both to explain in detail both how to use the app and to highlight the significance of participants' contributions, demonstrating the extent to which their data are valued and contribute to project goals (Bell et al., 2008; Evans et al., 2005; Land-Zandstra et al., 2016).

4.2. Citizen scientists' engagement

Overall, >20.000 records (11,876 "reports of mosquitoes", 8312 "reports of bites" and 538 "reports of breeding sites") were obtained from Italy in the study period, corresponding to 27 % of the total records in Europe. During the same time period 7066 "reports of mosquitoes", 5710 "reports of bites" and 8309 "reports of breeding sites" were obtained from Spain, where the Mosquito Alert app has been implemented since 2014. A systematic comparison between communication campaign and results achieved in the two countries is out of the scope of this paper. However, it may be hypothesized that the higher success in obtaining mosquito and bite reports in Italy was due the novelty of the app release compared to Spain. The large number of breeding sites is most likely due to the Mosquito Alert Educational Program run at schools in Spain, where kids produced local water drainer cartographies to help authorities on vector control in public spaces. The sampling effort - i.e. the expected number of participants who would send at least one record from a given sampling cell, an instrumental parameter to control for sampling biases and produce predictions of human-mosquito encounters (Palmer et al., 2017) - was highest in metropolitan areas and in the first two weeks of July.

The Italian records were contributed by approximately a third of registered participants, with an average of ~3 records/participant. The results obtained are similar to the 2.7 records/participant obtained with the Zanzamapp app (Caputo et al., 2020) active in Italy from 2016 to 2018. This was unexpected as the effort done per report by Zanzamapp participants was much reduced compared to Mosquito Alert reporting. This is so because the former did not include the possibility of attaching photos whereas the latter promotes records of mosquitoes with photos. The overall spatial coverage of the participants was 18 % of the total cells in Italy, for a total of 56 km^2, mostly concentrated in metropolitan areas. Highest coverage in urban areas has also been observed in citizen science projects focusing on biodiversity (e.g., iNaturalist, eBird, and eButterfly).

Press releases appear to have impacted the generation of records in ways similar to what we find for the recruitment of new participants. As already mentioned, a positive correlation between the number of media reports and the number of mosquito record submissions was shown in the analysis of the 'Muckenatlas' citizen science project (Pernat et al., 2022). However, our results also show that while online articles directly generated by Mosquito Alert ITALIA press releases (i.e. published within five days from press release) led to an increase in the number of participants and records, articles on mosquitoes briefly mentioning Mosquito Alert only (not derived from the press release) led to an increased number of app downloads, but not of reports. This suggests that the simple mention of the app in an article focusing on mosquitoes raises citizen scientists' curiosity about the app but does not successfully engage them in contributing to the project. It may be that successful engagement requires more detailed explanation of the project's objectives and implementation.

Approximately 2/3 of the participants did not send any record and most of those who sent records did it soon after having downloaded the app, with the engagement decreasing with participation time (11 % reporting propensity the first day after download) and approaching zero after ~50 days, consistent with the trend observed in Spain in the early phase of the project there (Palmer et al., 2017). Among participants who contributed sending at least one report, almost 50 % sent a single record and about 30 % sent ≥3 records. Only 4 % ($N = 260$) of participants submitted >10 records. These participation patterns were expected as long-term engagement is a recognized problem of citizen science projects. Sauermanna and Franzonib (2015) analysed data from seven citizen science projects and showed a rapid tendency toward a decline in citizen scientist contributions, which may be countered by outreach efforts or media attention.

Some specific factors could have contributed to citizen scientists' limited long-term engagement in the Mosquito Alert project. In particular, the fact that sending a record depends on a mosquito's actual presence, which is dependent on geographical and seasonal factors. A citizen scientist can be intrigued by the app and download it even in the absence of mosquitoes in its area and rapidly forget it, due to lack of the possibility to use it. Moreover, the effort needed to send photographic records of small flying insects is large enough to discourage participants from repeatedly engaging in the action, as demonstrated in mosquito citizen science project developed in Australia, where participants declares that the photography of mosquitoes is to be the greatest challenge (Braz Sousa et al., 2020).

In addition, the reward obtained (i.e. having the specimen identified by Entolab experts, the possibility to access an online map with all records and the point awards in the app) may not represent a sufficiently strong stimulus.

4.3. Citizen scientists' knowledge

The majority of the photos sent as "report a mosquito" actually corresponded to mosquitoes (i.e. 63 %). This proportion is in the range of those observed in other citizen science projects focused on mosquitoes, e.g. 70 % in Mückenatlas (Pernat et al., 2022) and 57 % in Muggenradar (Kampen et al., 2015).

Among the 8201 photographic records of mosquitoes examined by Entolab experts, 4914 were unambiguously identified as either *Ae. albopictus* (62 %) or *Culex* spp. (38 %). Overall, 86 % of citizen scientists' identifications as either *Aedes* invasive species or *Culex* spp. were confirmed by experts. Correct genus identification was higher in the case of records identified by citizen scientists as "Invasive *Aedes*" (94 %) than in the case of those identified as "*Culex* spp." (74 %). The capacity to correctly identify the mosquito genus increased with participation time, from 61 % at the beginning of app use to 75 % after 1 year, suggesting that the app use has an effect in enhancing participants' capacity to recognize mosquito morphological features.

5. Conclusions

This study shows a high level of recruitment in time and space of Italian citizen scientists in the Mosquito Alert project despite limited effort by the small Mosquito Alert ITALIA team using non-expert dissemination strategies. It suggests that citizen scientists can be effectively engaged in Italy to contribute to mosquito monitoring and control. The increased capacity of participants to distinguish between invasive *Aedes* species and *Culex* spp. over time highlights the educational value of the project.

Our models of dissemination activities suggest that higher success in citizen scientists' recruitment in a project on arthropod vectors can be obtained by:

i) focusing communication on the project goals and methods,
ii) stressing the project's public health significance and taking advantage of attention from independent news,
iii) carrying out dissemination activities synchronized to the seasonality of target species.

In addition, increasing local dissemination events to target audiences may have a high impact, although it appears that this works well only at local scales and through great efforts.

Our analysis also reveals that the majority of those who register do not further engage (by sending a report), and that even for those who do engage, their engagement decreases over time. Higher fidelity could likely be achieved by improving the app or, shortening feedback time to participants after they send a photographic record (already achieved in 2023 thanks to the inclusion of AI in the process), providing tangible rewards to the most active participants or improving the gamification strategies. However, the highest fidelity is expected to be achieved when Mosquito Alert app data become strategic for mosquito control optimization, which will be the strongest driver for a more continuous commitment by citizen scientists motivated by health concerns and a willingness to support mosquito control (Dekramanjian et al., 2023; Pernat et al., 2021).

To better understand the participation patterns in terms of quantity, quality, and spatial coverage, the Mosquito Alert team is developing specific metrics that can be associated to each participant's device, in a fully anonymized way. Future work will harness these metrics for improving communication strategies.

CRediT authorship contribution statement

C. Virgillito: Writing – original draft, Methodology, Formal analysis, Conceptualization. **E. Longo:** Data curation. **C.M. De Marco:** Data curation. **P. Serini:** Data curation. **M.V. Zucchelli:** Data curation. **F. Montarsi:** Data curation. **F. Severini:** Data curation. **R. Rosà:** Methodology. **D. Da Re:** Methodology. **F. Filipponi:** Formal analysis. **M. Manica:** Methodology, Formal analysis. **J. Palmer:** Methodology, Formal analysis, Conceptualization. **F. Bartumeus:** Conceptualization. **A. della Torre:** Writing – original draft, Conceptualization. **B. Caputo:** Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Some of the data that support the findings of this study are available on request from the corresponding author (BC). The data are not publicly available due to their containing information that could compromise the privacy of research participants. However, the open data used in this analysis have been deposited with Zenodo and may be accessed at https://doi.org/10.5281/zenodo.10649985.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.174847.

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