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Contributions of citizen scientists to arthropod vector data in the age of digital epidemiology

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Citizen-collected arthropod vectors are useful for epidemiological studies of vector–borne disease, especially since the vectors encountered by the public are the subset of vectors in nature that have a disproportionate impact on health. Programs integrating educational efforts with collecting efforts may be particularly effective for public health initiatives, resulting in an empowered public with knowledge of vector–borne disease prevention. Citizen science programs have been successfully implemented for the collection of unprecedented sample sets of mosquitos, ticks, and triatomines. Cyber infrastructure employed in digital epidemiology — including websites, email, mobile phone apps, and social media platforms — has facilitated vector citizen science initiatives to assess disease risk over vast spatial and temporal scales, advancing research to mitigate vector–borne disease risk.

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Introduction

Diseases in human and animal populations have a long history of standardized reporting (i.e. government-required notification of reportable or notifiable diseases), which generates datasets useful in epidemiological investigations to improve public and veterinary health. Such datasets have consolidated reports spanning decades (e.g. USGS WHISPers [1,2] and CDC WONDER databases [3,4]). Along with databases focused on disease reports, centralized long-term databases containing information for arthropod vectors are critical for identifying entomologic or acarologic risk of vector–borne disease, given spatio-temporal heterogeneity in vector occurrence, abundance, and infection (e.g. [5]). Despite the importance of such databases, there are a limited number of accessible large datasets of arthropod vectors with species-level identification in the US and beyond, owing in part to barriers in available resources including widespread field collection efforts and project funding.

To address vector-borne disease research needs, many research groups have turned to the public to help. Citizen science has long been used as a tool for public engagement in ecological research [6,7••]. Public participation in creating large arthropod vector collection datasets has been occurring for decades, but with rapid popularity given increased accessibility and communication in the digital era. Also described as community participation or crowdsourcing, the term 'citizen science' was added to the Oxford English Dictionary in 2014 [8]:

> Citizen science — scientific work undertaken by members of the general public, often in collaboration with or under the direction of professional scientists and scientific institutions

When applied to collections of arthropod vectors of public health importance, citizen science not only contributes to vector ecology studies, but also involves the public in the understanding and protection of their own health. Public participation in the collection of arthropod vectors comes with several advantages over researcher-led collection efforts (Box 1). Further, with the incorporation of data validation steps, citizen science collections are no less accurate than those collected by trained scientists and technicians [9,10].

The rapid expansion of technology based communication has facilitated a new era of disease investigation — digital epidemiology — which provides unique opportunities and challenges for addressing public health issues [11]. For example, mobile devices are being used to rapidly survey immature dengue virus mosquito vectors [12]. Websites such as HealthMap [13] and ProMED [14] aggregate infectious disease data from across the internet. Relevant health and vector data harnessed from rapidly expanding social media platforms, such as Twitter and Facebook, as well as mobile apps, provide access to unprecedented numbers of observations across vast

Box 1 Benefits and challenges of citizen science initiatives in the context of arthropod vector research

Benefits

- Data collected are epidemiologically relevant, being largely related to human-vector encounters.
- Collections from wider geographic areas than possible by small teams of scientists.
- Dual benefit of data collection and public education.
- Particularly useful for vectors that are low-density and/or difficult to collect using standardized efforts by research teams.
- Economical, as most programs do not pay contributors.
- Citizens are naturally interested in contributing information to scientific research, especially when also learning how to protect their own health.
- Relatively real-time data access.
- Data transparency facilitates open access.

Challenges

- Biases — project participants may not be representative of the broader population.
- Submission of incorrect specimens [32,38].
- Potential risk of infection during collection, transport, or shipment.
- Presence-only datasets, which are difficult to model. However, recent spatial analyses using machine learning and Bayesian approaches are circumventing these challenges [46–48].
- Misinformation and lacking information [19•].
- Managing and verifying data (pictures, specimens, or other records) so they are useful for future analyses
- Protecting anonymity/human use concerns, particularly when submitters may be sharing personal information.
- Obtaining dedicated funding for scientific staff to manage data may be difficult, and long-running programs need to develop training and data management protocols robust to varying skills of transient staff over the life of the program.
- Waning public interest/participation over time.

spatial scales. However, there are challenges in the use of these platforms for data collection or information dissemination; for example, an analysis of Zika-related posts on Facebook showed misleading posts received 10-times more views than factual information posted by public health organizations [15•].

This review outlines contemporary examples of arthropod vector citizen science efforts essential to establishing tick, mosquito, and triatomine collections, with examples of programs spanning Europe, Africa, Latin America, and the US. Further, we feature the integration of cyber infrastructure into citizen science programs.

Ticks

Ticks are vectors of diverse agents of disease (bacteria, viruses, protozoans) and account for the vast majority of reported cases of vector–borne disease in the US [16]. Regional knowledge of public encounters with various tick species across different seasons is critical for developing public health protection measures. Several initiatives by researchers and health departments harvest data from citizen encounters with ticks to learn about tick phenology, infection, and periods of heightened disease risk.

TickSpotters (http://www.tickencounter.org/tickspotters), a program run through the University of Rhode Island, tracks tick activity across North America. Citizen scientists save ticks removed from themselves or their pets, and participants submit tick photos through the website. Data are analyzed to answer research questions in tick biology (e.g. [17]) and are also fed into the Current Tick Activity app to help drive tick awareness. The resulting region-specific TickEncounter Index may be useful for individuals planning outdoor recreation or for raising medical community awareness for periods of high risk. A similar tick-collecting effort organized in Massachusetts led to a better understanding of tick phenology and pathogen infection prevalence, as well as duration of tick feeding, tick attachment sites, and ages of individuals bitten by ticks [18].

Another example is a national crowdsourcing tick collection initiative established in Finland in 2015, resulting in a Tickbank of nearly 20 000 *Ixodes* spp. from which three disease agents and new risk areas were identified [19•]. In the Netherlands, an effort to understand factors that determine tick bite risk used almost 35 000 geospatially-enabled reports provided by people who had been bitten by a tick; those data were analyzed to determine frequent environmental patterns associated with bites [20]. A recent effort validated tick identifications determined by entomologists who reviewed web-based digital photograph submissions versus the 'gold standard' method of specimen-based identification at the microscope. Over 97% of 284 high quality images were correctly identified to species; however only 74.3% of submitted images were considered of high enough quality to allow identification [21•]. Community-wide tick integrated pest management programs, with public involvement in tick surveillance, can improve the efficiency of tick control and reduce the risk of tick-borne disease [22].

Mosquitos

Recent epidemics of Zika, chikungunya, and other arboviruses, combined with the invasion of nuisance biting mosquito species, have emphasized the need for data on mosquito occurrence over multiple spatial and temporal scales. Citizen science programs provide key observations and specimens to vector control districts and researchers, resulting in early warnings about increasing abundance and a heightened ability for public health campaigns to prevent mosquito bites.

The Mosquito Alert program in Spain — developed to provide early warnings about Asian tiger mosquito (*Aedes albopictus*) invasion — compared citizen science data to traditional ovitrap surveillance. Citizen data provided early warning information about human-mosquito encounter probabilities of comparable quality to the traditional methods, but with larger geographic coverage and lower cost [23••]. The Invasive Mosquito Project, started by USDA Agricultural Research Service, compiled the largest crowd-sourced mosquito collection in the US [24]. This project includes a distinct educational component, with an interest in educating elementary and secondary school science classes about mosquitos while allowing students to submit mosquitoes to the national database [25••].

The Mosquito Mapper mobile phone application was designed with the goal of monitoring mosquito encounters in Berlin, Germany, and the publicly-available source code makes it possible to adapt to other urban environments [26]. Another recent effort proposes the use of mobile phones as acoustic sensors for high-throughput mosquito surveillance [27]. The species-specific wingbeat sounds are recorded by a mobile phone and compared to an established sound database. Initial field trials by citizen volunteers in California and Madagascar mapped spatial and temporal differences in mosquito activity, providing proof-of-principle that 'minimally trained users' could map mosquito locations using low-cost mobile phones. The recent US-based mobile 'Kidenga app' leverages community participation across the southern US in the reporting and tracking of vector-borne disease symptoms and also gathers data on mosquito breeding sites [28].

Citizens in Baltimore were recruited to assess potential mosquito habitats and evaluate mosquito nuisance [29•]. Those individuals who submitted a season-worth of data were awarded $100 for project participation. Citizen-reports of mosquito nuisance closely matched the rise and decline of mosquitos trapped by the research team.

Triatomine insects

Triatomine insects (Reduviidae: Triatominae) are vectors of *Trypanosoma cruzi*, etiologic agent of Chagas disease in humans and other animals. These nocturnal insects, colloquially known as 'kissing bugs', are found across Latin America and in 28 US states [30]. While standardized trapping methods exist for other vectors (e.g. light and CO_2 traps for mosquitos, and cloth dragging for ticks), no such collection technique is similarly reliable for collecting triatomines. Many successful control and elimination programs in Central and South America have relied on public sampling of triatomines to indicate house re-infestation and establish collections for research purposes [31].

A study in the early 1940s in Arizona went so far as to offer financial reward for triatomines, with a campaign slogan stating, 'Nab that bug at one cent each for Dr. Wood at City College to keep.' [32]. More recently, a targeted bug hunting campaign in Guatemala encouraged participation using lottery tickets [33]. Other studies have relied on collections by the public [34–39]. Community participation yielded higher sensitivity and lower costs for monitoring homes for vector re-infestation than active searches or use of vector-detection devices [10,40]; further, community participation is expected to avert cases of Chagas disease due to early detection of vectors in homes [41]. Efforts in Yucatan, Mexico, raised familial awareness and contributions to citizen science initiatives through targeting schoolchildren [42•,43].

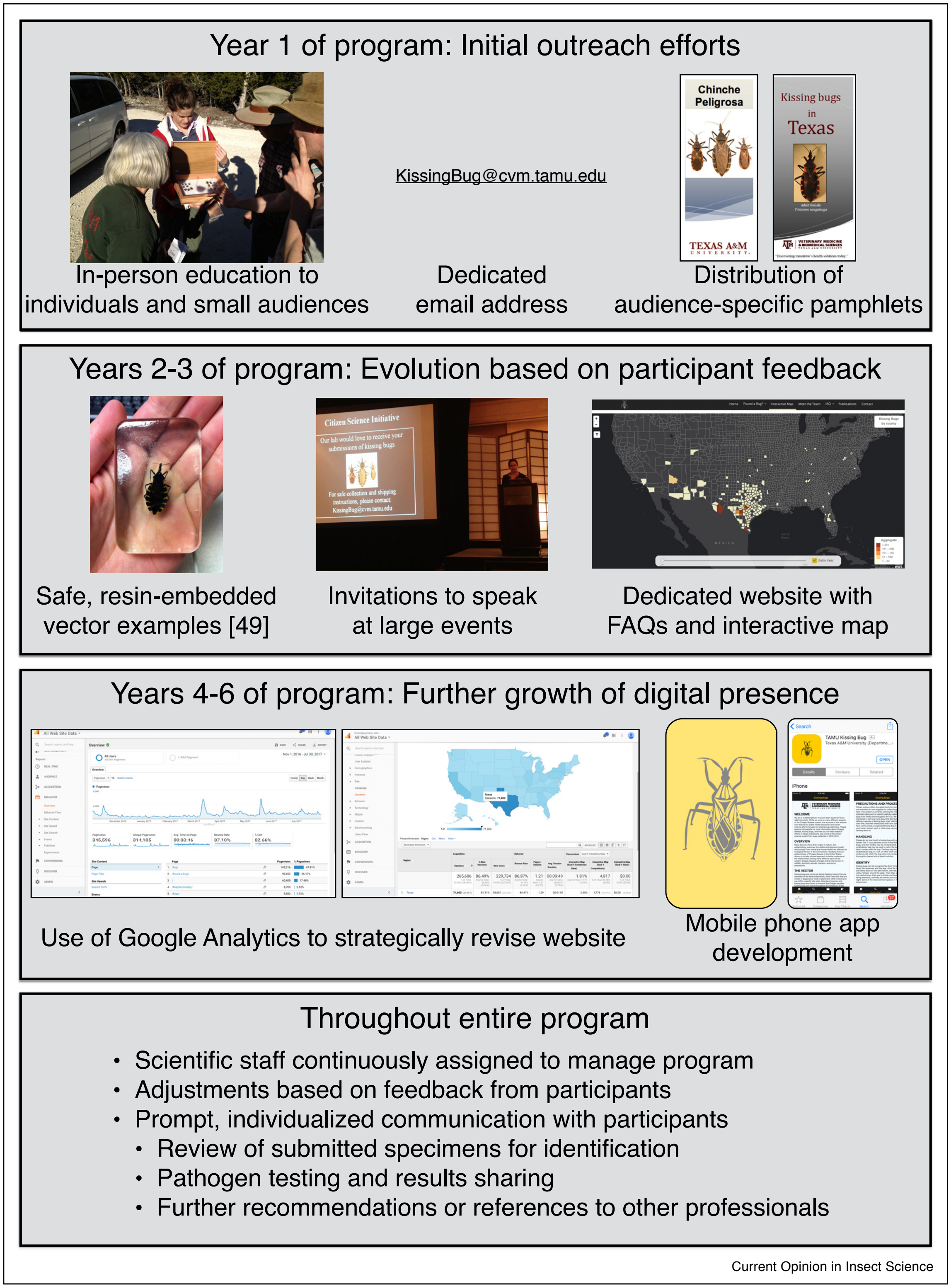
We built a citizen science program to facilitate research on triatomines and Chagas disease risk, with an initial focus on Texas and expansion to the southern US [39] (Figure 1). Through a combination of outreach campaigns [49] and cyber infrastructure, citizen scientists generated an unprecedented collection of triatomines in the US, spanning 18 states and currently available for research purposes. Data were used to describe geographic distribution and natural history of triatomines [44] as well as infection prevalence and circulating strains of *T. cruzi* [45]. The program website is currently the top hit on major internet search engines for the search string 'kissing bug', generating approximately 1000 visitors per day.

Discussion

Citizen science has advanced vector research, expanding the temporal and geographic scope of field-based vector investigations. Because citizen science initiatives often prioritize public education, the dual benefit is an empowered public better able to protect themselves from vector–borne disease, and an enabled research community. Common themes in contemporary, high profile arthropod vector citizen science initiatives include the use of attractive websites to educate the public, solicit public submission of data, and disseminate research findings, often as maps showing vector occurrence (Figure 2).

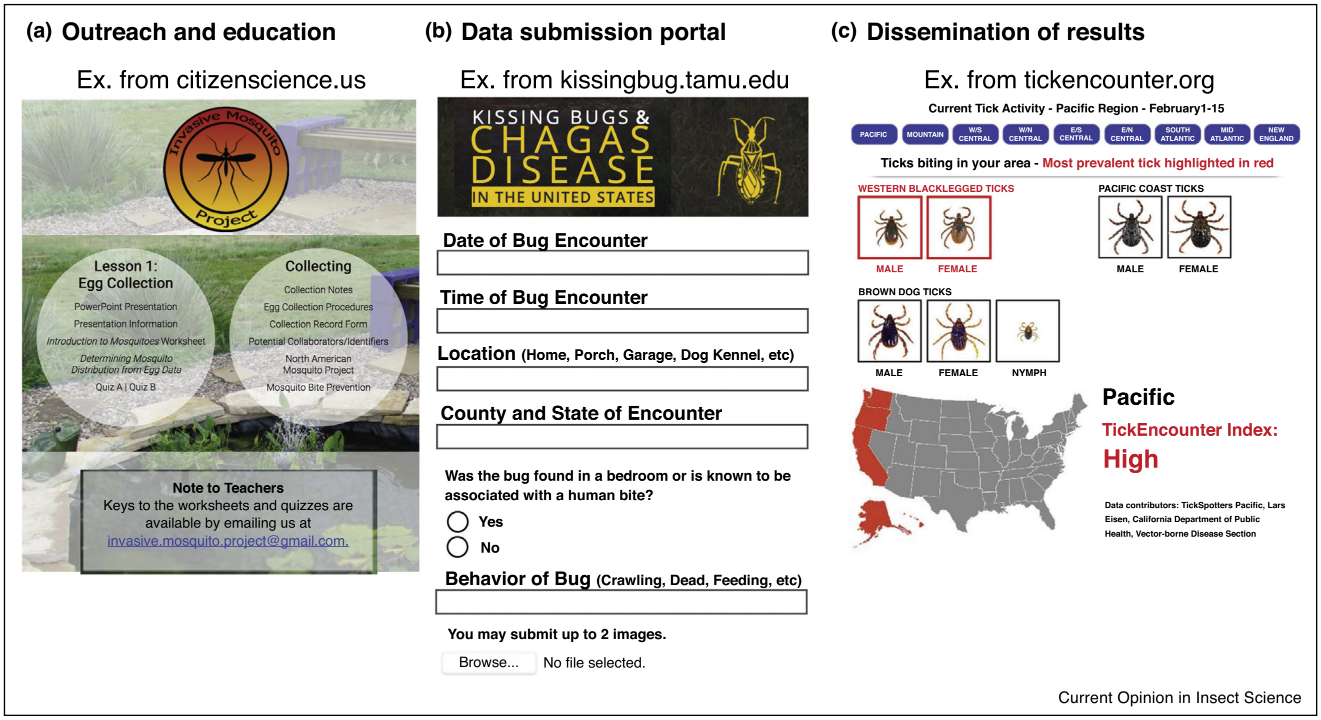
Among the benefits of the citizen science approach (Box 1) include transparency and relatively real-time availability of data to the public. Further, by definition, citizen scientists collect vectors that they encounter; this subset of vectors has high epidemiological relevance and represents the vectors most likely to transmit disease agents to humans. The citizen science approach is, however, challenged by significant limitations, including those that arise from managing vast amounts of opportunistically-collected data (Box 1). Effective management and verification of data (such as through photographs, specimens, or recordings) is necessary to ensure the quality of analyses; in the absence of data verification, the reliability of data may be unknown. A critical challenge of citizen science efforts is participant recruitment, particularly determining individual motivating factors. Some examples in this review used financial/prize incentives [29•,32,33]. In our own triatomine program, most people are incentivized by learning the pathogen testing results of specimens they collected, at no charge to the submitter. Optimal ways to recruit and retain participants will need to be assessed and regularly evaluated on an individual program basis.

Figure 1



The Texas A&M University Kissing Bug Citizen Science Program, a collaborative effort among the Department of Entomology, College of Veterinary Medicine, and Texas Department of State Health Services, has grown from initial efforts to educate the public across private ranches and along the Texas-Mexico border to a program that amassed the largest collection of triatomines in the US representing 18 states.

Figure 2



Web interfaces for vector citizen science programs in the US share common attributes including: outreach and educational information; data submission portals for participants to input observations and upload photos for identification; and dissemination of research findings in the form of measures of relative vector abundance or activity. **(a)** The Invasive Mosquito Project encourages school teachers to educate elementary students about mosquito habitats; students submit egg rafts for identification. **(b)** The Kissing Bug and Chagas Disease Project collects citizen photos of triatomine vectors as a precursor to mailed specimens that are tested for the *T. cruzi* parasite. **(c)** The TickSpotters program calculates biweekly, regional tick encounter indices based on community reports of tick bites that are useful to the public for planning outdoor recreation.

Recent initiatives have promoted a centralized national database in the US for vector data [46]. Successful integration of large regional vector datasets will require top-down and bottom-up support. Top-down support must come from federal and state agency investment, whereas bottom-up support will need to be facilitated by local agencies and academic partners. Ideally, centralized data repositories will allow agencies and researchers to observe trends and events in neighboring regions. Fortunately, many publishers and researchers are adopting a new culture of open access data and visibility, leading to consortiums like Vectorbase (https://www.vectorbase.org/) and individual lab initiatives (https://andersen-lab.com/secrets/data/zika-genomics/). We urge researchers managing citizen science initiatives to lead the movement toward data sharing, enabling increased predictive ability and protection of human and animal health.

Given today's pressing environmental and public health stressors — including emerging pathogens, invasive species, and climate change — contemporary information on changing vector distributions across different temporal and spatial scales is critical for assessing vector–borne disease risk and developing public health policies. The merging of citizen science and digital epidemiology has the potential to revolutionize vector–borne disease research and public health protection.

Conflict of interest statement

Nothing declared.

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