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Benefits and Drawbacks of Citizen Science to Complement Traditional Data Gathering Approaches for Medically Important Hard Ticks (Acari: Ixodidae) in the United States

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Abstract

Tick-borne diseases are increasing in North America. Knowledge of which tick species and associated human pathogens are present locally can inform the public and medical community about the acarological risk for tick bites and tick-borne infections. Citizen science (also called community-based monitoring, volunteer monitoring, or participatory science) is emerging as a potential approach to complement traditional tick record data gathering where all aspects of the work is done by researchers or public health professionals. One key question is how citizen science can best be used to generate high-quality data to fill knowledge gaps that are difficult to address using traditional data gathering approaches. Citizen science is particularly useful to generate information on human–tick encounters and may also contribute to geographical tick records to help define species distributions across large areas. Previous citizen science projects have utilized three distinct tick record data gathering methods including submission of: 1) physical tick specimens for identification by professional entomologists, 2) digital images of ticks for identification by professional entomologists, and 3) data where the tick species and life stage were identified by the citizen scientist. We explore the benefits and drawbacks of citizen science, relative to the traditional scientific approach, to generate data on tick records, with special emphasis on data quality for species identification and tick encounter locations. We recognize the value of citizen science to tick research but caution that the generated information must be interpreted cautiously with data quality limitations firmly in mind to avoid misleading conclusions.

Keywords

Ixodidae; citizen science; tick data collection; tick surveillance

Background

Tick-borne diseases are increasing in North America (Rosenberg et al. 2018). Major human-biting ixodid tick species—*Ixodes scapularis* Say, *Ixodes pacificus* Cooley and Kohls,

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Amblyomma americanum (L.), *Amblyomma maculatum* Koch, *Dermacentor variabilis* (Say), *Dermacentor andersoni* Stiles, *Dermacentor occidentalis* Marx, and *Rhipicephalus sanguineus* sensu lato (Acari: Ixodidae)—collectively serve as vectors for more than 15 human pathogens, ranging from viral to bacterial and parasitic agents (Eisen and Paddock 2020). The most basic risk factors for human exposure to a tick-borne disease agent are whether or not 1) a human-biting tick species capable of transmitting the pathogen in question is present in the local environment and 2) the pathogen occurs in the local populations of one or several human-biting vector tick species. Most areas of the United States where human populations are concentrated harbor at least one commonly human-biting vector tick species (Eisen et al. 2017, Eisen and Paddock 2020) and many states are home to several different human-biting vector species (Merten and Durden 2000, Jordan and Egizi 2019). Notably, distributions of medically important ticks and their pathogens change over time, necessitating ongoing data collection. Up-to-date knowledge of which tick species and associated pathogens are present in the local environment and when each tick life stage is actively host-seeking is helpful for outreach campaigns to inform the public and medical community about when and where people are at risk for exposure to ticks and tick-borne pathogens. Additionally, human behavior strongly influences the risk for tick bites (Hook et al. 2015, Eisen and Eisen 2016, Aenishaenslin et al. 2017, Stafford et al. 2017, Mead et al. 2018, Fischhoff et al. 2019, Jordan and Egizi 2019). These fundamental facts, together with the understanding that geographic distributions and population dynamics of vector ticks are dynamic (Randolph 2004, Ogden et al. 2018, Sonenshine 2018, Gaff et al. 2020), must be considered when deciding how to most effectively improve our knowledge of where, when, and why humans are bitten by ticks potentially carrying disease agents.

In this Forum article, we explore how citizen science may be used to complement traditional tick data collection, where all aspects of the work are conducted by researchers or public health professionals, to improve the understanding of risk for human bites by potentially pathogen-infected ticks. Two basic themes are of crucial importance when exploring this topic: 1) data quality, including for tick species identification, pathogen detection methodology, and spatial precision of the tick encounter location, and 2) judicious interpretation of information to account for the limitations of the methodology used to generate the data. We first outline basic characteristics of different methods to gather tick-associated data and then discuss how this relates to citizen science.

Characteristics of Different Approaches to Gathering Tick-Associated Data

Epidemiological public health surveillance refers to the ongoing, systematic collection, analysis, and interpretation of health-related data (Thacker and Birkhead 2008). The term surveillance is used more loosely in relation to ticks and pathogens found in ticks. Systematic tick sampling and pathogen detection efforts are often of short duration, for example as part of research projects, rather than ongoing activities spanning many years or decades. However, compilation of these short-term studies can reveal significant trends (Dennis et al. 1998, Springer et al. 2014, Eisen et al. 2016, Lehane et al. 2020). Examples from the United States of long-term surveillance efforts, spanning 4 to >20 years, include collection of host-seeking ticks in fixed sampling sites in Maine (Elias et al. 2020), Minnesota (Bjork et al. 2018), and New York (Prusinski et al. 2014; New York State

Department of Health [NYSDOH] 2020a,b), and submission of ticks recovered from humans or domestic animals to tick identification or tick identification and pathogen testing service programs in Connecticut (Little et al. 2019, Little and Molaei 2020), Maine (Rand et al. 2007, Elias et al. 2020), Massachusetts (Xu et al. 2016), Michigan (Walker et al. 1998), New Jersey (Jordan and Egizi 2019), Rhode Island (Johnson et al. 2004), the Pacific Coast states (Xu et al. 2019), or U.S. Army bases across the eastern United States (Rossi et al. 2015). Similar long-term surveillance programs for host-seeking ticks or ticks recovered from humans or domestic animals have been implemented in Canada (Ogden et al. 2006, 2010; Ripoche et al. 2018; Gasmi et al. 2019; Chilton et al. 2020) and Europe (Garcia-Marti et al. 2017a, b, 2018; Cull et al. 2020; Springer et al. 2020). Moreover, efforts are underway in the United States to strengthen the national capacity for systematic and sustained surveillance of human-biting ticks and their associated disease agents (Centers for Disease Control and Prevention [CDC] 2018, 2020; Eisen and Paddock 2020).

Tick surveillance is often classified as active versus passive but as some tick collection methods do not easily fit into this classification scheme, we prefer to use more descriptive terms when describing different collection approaches. Table 1 summarizes key characteristics of different approaches for collection of ticks and detection of pathogens in the ticks, focusing on factors that describe how tick and pathogen data are generated and influence how they can be interpreted. The initial dichotomy is whether the tick collection method is ‘fully quantitative’, yielding both a numerator and a denominator, or ‘opportunistic and semi-quantitative’, producing quantitative data for only the numerator or denominator. Examples of outcome measures from commonly used tick collection methods producing fully quantitative results include the number of host-seeking ticks collected per trap-day or unit area/time covered by walking, dragging, or flagging samples; the number of ticks collected per live or recently killed wild or domestic animal; or the number of recorded tick bites or tick encounters per person and unit of time for participants in a research study where such information is specifically recorded. There is a plethora of publications describing the results of such tick collection methods from North America and Europe.

Tick collection methods best defined as opportunistic and semi-quantitative based on quantitative data being collected for the numerator (number of ticks recovered) while the denominator remains unknown include 1) submission from the public of ticks collected from humans to public service tick identification or tick identification and pathogen detection programs, where the number of individuals that were aware of the program and would have submitted ticks had they been encountered are unknown (Walker et al. 1998; Johnson et al. 2004; Rand et al. 2007; Xu et al. 2016, 2019; Nieto et al. 2018; Jordan and Egizi 2019; Little et al. 2019; Elias et al. 2020); and 2) opportunistic recovery of ticks from livestock or pets by members of the public or veterinarians during daily activities or routine health checks, without knowledge of the total number of animals that were examined for presence of ticks (Jaenson et al. 1994; Tälleklint and Jaenson 1998; Walker et al. 1998; Guerra et al. 2001; Johnson et al. 2004; Ogden et al. 2006, 2010; Raghavan et al. 2007; Rand et al. 2007; Hamer et al. 2009; Rhea et al. 2011; Abdullah et al. 2016; Hendricks et al. 2017; Laaksonen et al. 2017; Cull et al. 2018; Lee et al. 2019; Saleh et al. 2019; Chilton et al. 2020). Another tick collection method best defined as opportunistic and semi-quantitative is the recovery of ticks from road-kill animals (Lorusso et al. 2011, Szekeres et al. 2018), where the denominator can be quantified as the number of examined animals but where an unknown proportion of ticks may have already dislodged from the carcasses before they were recovered and examined for ectoparasites.

Another important factor to consider is whether the ticks were collected while seeking a host versus recovered from a host, including wild animals, domestic animals, or humans (Table 1). This distinction has implications both for the spatial interpretation of the tick collection record and the detection of pathogens in the ticks. Collection of host-seeking ticks from the environment provides records with very high spatial precision for the location where the tick was contacted, regardless of whether it was collected by drag or flag sampling (the drag/flag is checked at regular, short intervals based on distance traveled or time elapsed), during walking sampling (coveralls are checked at regular, short intervals based on distance traveled or time elapsed), or via trapping (ixodid ticks have limited capacity for horizontal movement toward a stimulus). The geographical location where contact was first made between a tick and the host it was recovered from is more challenging to determine as it depends on the spatial activity range of the host species and the time elapsed since the tick encountered the host. The spatial precision for the initial tick encounter location is high for host species with limited activity ranges (for example, livestock confined to a pasture or rodents) but less spatially distinct for mammals with larger home ranges (for example, deer and medium-sized carnivores) and resident or, especially, migrating birds. For people and pets, there is the added challenge of needing to account for travel history when attempting to pinpoint the likely geographical location where a tick found crawling or attached was first encountered. For attached ticks, the degree of engorgement can be useful to estimate the duration of time (number of days) elapsed since the tick found its host and attached (Piesman and Spielman 1980, Yeh et al. 1995, Falco et al. 1996, Gray et al. 2005, Meiners et al. 2006).

As outlined in Table 1, the source of the collected ticks also influences the interpretation of detected pathogens. For a pathogen detected in a fed tick (of any life stage) recovered from an animal host, it often is not clear whether the tick was infected before starting to feed or if it acquired the pathogen while feeding. Not all wild animal species, livestock species, or pet species serve as reservoirs for a given tick-borne pathogen; the pathogen detection result therefore should be interpreted bearing in mind the reservoir competency of the host animal for the pathogen in question as well as whether the pathogen is passed transovarially in the tick species in question. Moreover, as noted previously for Lyme disease spirochetes (Eisen 2020), pathogens acquired during a blood meal may be passed transstadially through the molt for some, but not all, tick species that infest reservoir animals. Pathogen detection in host-seeking nymphs or adults has the clear advantage of indicating that the pathogen survived the molt and was present in the tick as it sought a new blood meal host. The final consideration then becomes whether the tick species in question is capable of transmitting the transstadially passed pathogen while taking a blood meal: this is often, but not always, the case across combinations of tick and pathogen species.

Citizen Science and Tick Collection Records

As outlined in the Crowdsourcing and Citizen Science Act of 2016 (15 USC 3724), citizen science is increasingly recognized by federal agencies in the United States as an approach with potential to accelerate the generation of research data. An official government website (https://www.citizenscience.gov/#) was developed to catalog federally supported citizen science projects and provide resources to connect researchers with citizen science coordinators and practitioners. There are different definitions for the term citizen science (also known as community-based monitoring, volunteer monitoring, or participatory science), but common themes include the participation of non-scientists in data collection, compilation, and/or analysis, most often in collaboration with formally trained academic or federal scientists (Cohn 2008, Kullenberg and Kasperowski 2016, Bartumeus et al. 2018, Hamer et al. 2018). The longest standing citizen science project in the United States is the Cooperative Observer Program operated by the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration. Non-scientist volunteers have documented local weather-related data for this federal program for more than a century since its launch in 1890 (NWS 2020). Two important aspects of this highly successful citizen science program to aid in local weather data collection are that: 1) it allowed for logistically feasible and minimal cost measurement of weather data across a large number of localities long before weather stations were capable of automated measurements and 2) the core data collected—including daily maximum and minimum temperatures and 24-h rainfall or snowfall—are straightforward and can be measured and recorded using simple, standardized equipment. The question then becomes to what extent such general beneficial aspects of a successful citizen science program can be translated to efforts involving collection of data on human-biting ticks.

At the time of this writing, the online catalog of federally funded citizen science programs (https://www.citizenscience.gov/catalog/#) includes two projects specifically focused on mosquitoes and mosquito-borne disease (‘The Invasive Mosquito Project: A Public Education Tool’, sponsored by the U.S. Department of Agriculture, and ‘U.S.-Mexico Border Early Warning Disease Surveillance for Dengue and Chikungunya’, sponsored by the Centers for Disease Control and Prevention). Citizen science is playing an increasing role in research on the distribution of mosquito species of medical importance and their control, with recent studies from North America (Maki and Cohnstaedt 2015, Jordan et al. 2017, Johnson et al. 2018, Tarter et al. 2019) as well as Europe (Kampen et al. 2015, Heym et al. 2017, Palmer et al. 2017, Walther and Kampen 2017, Eritja et al. 2019), Africa (Murindahabi et al. 2018), and Australia (Braz Sousa et al. 2020).

The online catalog of federally funded citizen science programs does not currently include any projects involving ticks or tick-borne diseases but there are examples of projects run by academic institutions, non-profit organizations, and county, state, or federal entities where tick data or tick specimens provided by members of the public/citizen scientists were used to further the knowledge of human-biting ticks. Three different approaches were used in these projects to identify ticks that members of the public found crawling on or biting people or pets: 1) physical submission of ticks to professional scientists for tick identification and, in some cases, pathogen detection, 2) submission of digital tick images to professional scientists for tick identification, and 3) submission of tick information where species and life stage identification was done by the citizen scientist submitter with various aids, such as online guides showing images of different tick species and life stages.

One example from the first category of projects involving members of the public is a study from Sweden in the early 1990s where the public was engaged to submit collected ticks—including the primary human-biting tick in Sweden, *Ixodes ricinus* (L.)—to a research project where the professionally identified ticks then formed part of the overall database to define the geographical distributions of ixodid and argasid tick species across the country (Jaenson et al. 1994). Requests for physical tick submissions from the public for the specific purposes of the collection records to inform which tick species and life stages bite humans or pets or to form part of a database to define the broad geographical distributions of tick species (and in some cases also the associated pathogens found in the ticks) were also employed by other researchers in the United States, Canada, and Europe (Smith et al. 1992, Walker et al. 1998, Goddard 2002, Ogden et al. 2006, Gleim et al. 2016, Laaksonen et al. 2017, Cull et al. 2018, Lewis et al. 2018, Nieto et al. 2018, Jongejan et al. 2019, Lernout et al. 2019, Porter et al. 2019, Saleh et al. 2019, Salkeld et al. 2019, Chilton et al. 2020).

Another primary reason for requesting physical tick submissions from the public has been the establishment of service programs that, freely or at-cost, provide professional tick identification services, and sometimes also pathogen detection services, and communicate the findings back to the individual submitters. Examples of non-commercial entities in the United States that have provided such public service programs over time periods spanning many years include the Connecticut Agricultural Experiment Station (Little et al. 2019; Little and Molaei 2020; Connecticut Agricultural Experiment Station [CAES] 2020a,b), the Maine Medical Center Research Institute (Rand et al. 2007, Elias et al. 2020), the Monmouth County Mosquito Control Division (Jordan and Egizi 2019), the New Hampshire Department of Agriculture, Markets & Food (https://www.agriculture.nh.gov/divisions/plant-industry/tick-identification.htm), the Texas Department of State Health Services (https://www.dshs.texas.gov/idcu/health/zoonosis/tickBites/), the University of Rhode Island Tick Research Laboratory (Johnson et al. 2004), the University of Massachusetts, Amherst (Xu et al. 2016, 2019), and the U.S. Army Public Health Command (Rossi et al. 2015). Data obtained from ticks submitted by citizens to such public service tick identification/pathogen detection programs have secondarily been used to 1) clarify which tick species and life stages bite humans, when during the year peak human-biting occurs, and where on the human body tick bites most often occur; 2) describe changes over time for annual numbers of human bites by different tick species; and 3) assess whether data on human bites by vector ticks can predict spatial and inter-annual patterns of tick-borne disease case incidence.

The best example of the second category of programs involving members of the public, where the tick itself is not submitted but rather identified by a professional entomologist from a digital image provided by a member of the public together with tick encounter information, is the TickSpotters service provided through the University of Rhode Island TickEncounter Resource Center (https://tickencounter.org/; Kopsco et al. 2020). The final category, where members of the public identify the encountered ticks themselves and provide data on species and life stage together with additional information relating to the tick encounter, is represented by online data collection tools such as the Vermont Tick Tracker (https://apps.health.vermont.gov/vttracking/ticktracker/2019/d/index.html) and recently launched apps such as the The Tick App (https://thetickapp.org/; Fernandez et al.

2019) and the TickTracker App (https://livlymefoundation.org/ticktracker-app/). In the sections below, we place these existing approaches to engage the public in gathering of tick-related data into the broader context of how citizen science best can help improve our knowledge of tick distributions and how to prevent tick bites and tick-borne disease.

Incorporation of Citizen Science-Derived Information Into Tick Record Databases and Tick Distribution and Abundance Maps

Maps are a means for sharing graphical information on where a given tick species can be encountered or for depicting acarological risk of encountering ticks; the accuracy of the presented map directly reflects the quality of the data used to generate the map. This is equally true for maps based on data for actual tick records and maps showing model-derived projections for tick presence or abundance. Because tick records are generated in a variety of contexts, there is a need to decide which data to include versus exclude in a database being compiled for the specific purpose of generating maps depicting spatial tick distributions or tick abundance patterns. Primary considerations include 1) the perceived quality of the species and life stage identification for the tick record and 2) the source from which the tick was recovered to inform whether or not the tick record is relevant at the level of spatial granularity a map depiction aims to achieve. The expected likelihood of a correct tick species and life stage identification is very high when the tick specimen is physically accessible for examination by a professional scientist trained in tick identification or if the specimen is identified using molecular assays that compare sequence data to reference sequences. Using other methods, the expected likelihood of a correct identification falls to moderate–high when the professional scientist identifies the tick from a submitted digital image (the identification is influenced by both the quality of the image and the level of experience of the person viewing it) and to low when the identification is made by a citizen scientist without formal training. In a real-world scenario, ticks often have been attached for some period of time before being detected and removed, and also may have been damaged in the removal process. Compared with unfed ticks, partially or fully engorged ticks may be more difficult to identify without access to a high-quality stereo microscope. In scenarios that also include detection of pathogens in submitted ticks, typically done via detection of pathogen genetic material, additional concerns include the quality of the pathogen detection algorithm and the level of experience of the laboratory staff. Testing of ticks for presence of human pathogens is done across a wide range of federal, state, academic, and private laboratories but, as noted in a recent national survey on tick surveillance and control practices (Mader et al. 2020), there is currently no certification or accreditation process to ensure a quality standard for the pathogen detection results.

Another important consideration when compiling a geographical database with the intent of generating a tick distribution or abundance map is the distinction between absence of the tick and lack of data records. In compilations of national scale data to generate county-level distribution maps for key human-biting ticks in the United States, we therefore use the categories of established, reported, and no records (Dennis et al. 1998, Springer et al. 2014, Eisen et al. 2016, Lehane et al. 2020). Due to lack of standardized national surveillance for ticks in the United States until very recently (CDC 2018, 2020; Eisen and Paddock 2020;

Mader et al. 2020), some counties located within model-projected distributions for a given tick species but lacking tick presence records likely fall in the category of no tick records due to inadequate tick collection efforts rather than the tick species truly being absent. From a public health standpoint, incorrect depiction in a map of tick absence for an area where the tick species actually is present is problematic because it may lead to decreased vigilance for use of personal protective measures to prevent tick bites.

As long as a high-quality tick identification method is used, tick records resulting from efforts involving citizen scientists have clear potential to help fill in gaps in existing tick distribution maps, especially in areas where a tick species is present but rare and therefore may not be easily recovered during routine drag/flag sampling-based tick surveillance efforts. Such involvement by citizen scientists are similar to the previously mentioned Cooperative Observer Program operated by the National Weather Service, as the citizen scientist tick collections facilitate data gathering across a greater number of specific locations than otherwise possible. However, it is important to follow up citizen science-derived tick species records of special interest with drag/flag sampling to confirm that the given tick species indeed is present in the local environment. This specific strategy was used to complement backyard adult mosquito collections by citizen scientists in the Netherlands, where mosquito records of special interest, for example the invasive *Aedes japonicus japonicus* (Theobald), were followed up by additional collection efforts targeting larval or adult mosquitoes in the local environment (Walther and Kampen 2017).

Ticks recovered from people or pets (especially dogs) come with the added challenge of travel potentially masking the actual location where the tick encounter occurred. Unless detailed travel histories are available for the period of time when the tick encounter may have occurred, and bearing in mind that people often underestimate the amount of time a tick has been attached before it is discovered (Sood et al. 1997, Logar et al. 2002, Wilhelmsson et al. 2013), the tick encounter location may not always be reliably determined even at the coarse county scale. A similar problem with determining finer-scale tick encounter locations occurs for ticks recovered from wild mammals with large home ranges and birds, especially during their migration seasons.

The quality of information included in a database for geographical tick records is strongly influenced by the characteristics of the tick identification process, together with the spatial precision for the initial tick encounter location. Overall, the highest quality data are represented by ticks that were physically accessible to a professional scientist for species identification (molecular or morphological) and where the collection method allows for fine-scale determination of the host-seeking location of the tick specimen (for example, drag sampling with locations of the drag samples recorded). Further classifications that downgrade the overall quality of a tick record (for example, tick species identification by a citizen scientist or the tick source being a human without a known travel history) are not intended to reflect poorly on any currently used method to collect data on tick records but rather to caution against interpretations that go beyond what is reasonable based on the reliability of the underlying data. Perhaps the most difficult data quality classification problem is for digital tick images examined by a professional scientist trained in tick identification. This method can have very high (>95%) species identification accuracy for commonly encountered tick species, such as *A. americanum*, *D. variabilis*, and *I. scapularis*, when high-quality images of correctly positioned ticks are viewed by professional entomologists experienced in identifying ticks from digital images (Koffi et al. 2017, Kopsco et al. 2020). However, in more general terms, identification of ticks from digital images is highly sensitive to both image quality (resolution, contrast, and tick positioning) and the level of experience of the individuals responsible for the tick identification. The method also may be prone to misclassify less commonly encountered locally established or invasive tick species that can be confused with more common species based solely on a digital image.

Citizen Science-Derived Information About Human–Tick Encounters

Recovery of ticks found crawling on or biting humans is perhaps the most intriguing aspect of citizen science because it provides unique data that are rarely generated without the aid of citizen scientists. Collection of ticks from humans has the distinct benefit, relative to collection of host-seeking ticks, of providing information on actual encounters with ticks (or infected ticks if they also are tested for pathogens) resulting from daily life. Collected ticks must be identified to species because most areas of the United States harbor multiple human-biting tick species (Merten and Durden 2000). Using set ratios for different tick species based on historical data for human–tick encounters as a proxy for species identification (for example, 80% *I. scapularis* and 20% *D. variabilis*) is not reliable because population dynamics are not synchronized across years between human-biting tick species with different host preferences and life-cycle durations (Walker et al. 1998, Rand et al. 2007, Jordan and Egizi 2019, Pak et al. 2019, Elias et al. 2020) and additional tick species may be increasing in importance as human-biters over time, as seen for *A. americanum* in New Jersey and *D. variabilis* in Maine (Jordan and Egizi 2019, Elias et al. 2020). Moreover, data for ticks recovered from humans are likely to be skewed toward collection of adult ticks (larger and easier to spot compared to immatures) and tick species with more noticeable bites (for example, ticks with longer mouthparts). Conversely, as indicated by Lyme disease patients often being unaware of a tick bite preceding the onset of symptoms (re-viewed by Eisen and Eisen 2016), the immature stages of some tick species—including *I. scapularis* for which the nymphs are recognized as the primary vectors of Lyme disease spirochetes to humans—are very likely underrepresented in collections from human hosts. This limitation, together with potential uncertainty in the spatial location where the tick was initially encountered, must always be considered when interpreting data on ticks recovered from humans. Long-term data sets on ticks recovered from humans are especially valuable as they can provide crucial insights into human–tick encounters, not only for the general seasonal patterns for encounters with different tick species and life stages, and where on the human body most bites occur, but also for changes over time to the tick species most commonly encountered by humans and the prevalence of pathogens harbored by different tick species recovered from humans (Rand et al. 2007; Xu et al. 2016, 2019; Jordan and Egizi 2019; Little et al. 2019, Elias et al. 2020).

Data Quality Considerations

In this age of increasing possibilities for rapid data collection via emerging technologies (for example, smartphone apps) and ongoing proliferation of scientific journals with variable standards for peer review, it is easier than ever before to collect large amounts of data and publish the findings of a study. Moreover, there now also is the possibility of publishing manuscripts in a citable format on pre-print servers (for example, https://www.biorxiv.org/) prior to peer review in a scientific journal. Data quality, therefore, must be a primary concern going forward and this should include all aspects of data collection. In the specific case of citizen science and ticks, main potential problems include tick species identification by citizen scientists without corroboration by professional scientists and lack of travel histories for humans or pets during the period of time when a tick discovered biting may have initially been encountered. This is not intended as a criticism of either citizen scientists or data collection via smartphone apps but rather as a reminder to both professional scientists and citizen scientists to be judicious in the interpretation of data collected via emerging technologies and involving distinctions that are difficult to make unless you have specific training. When used to best effect, citizen science could be a powerful force in the continuing struggle to reduce the negative societal impacts of ticks and tick-borne diseases. This is balanced against the risk for citizen science projects to generate poor quality data (for example, through tick species identification by citizen scientists) and potentially misleading information (for example, incorrect tick encounter locations) if used without adequate data quality safeguards and cautious interpretation of project results.

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Table 1.

Key characteristics of different approaches for collection of ticks and detection of pathogens in the ticks

Classification of tick collection approach	Source of ticks	Examples of tick collection methods	Spatial interpretation in relation to source of recovered tick	Pathogen interpretation in relation to source of recovered tick
Fully quantitative (numerator and denominator)	Environment	Systematic collection of host-seeking ticks by dragging/flagging or walking while wearing coveralls; or by tick trapping	Fine-scale determination of tick encounter location	Infection indicative of transstadial passage of pathogen following infectious blood meal[d]
Fully quantitative (numerator and denominator)	Wild animals	Systematic tick collection from captured vertebrates or hunter-killed deer	Tick encounter location falling somewhere within the spatial activity range of the host species the tick was collected from	Not clear if the tick already was infected before the blood meal or acquired the pathogen while feeding; not indicative of transstadial passage of pathogen[e]
Fully quantitative (numerator and denominator)	Livestock (e.g., cattle, sheep, and goats)	Systematic tick collection from a defined livestock population	Tick encounter location falling within readily defined host movement range, unless livestock were moved by vehicle during the time period when tick encounter may have occurred	Not clear if the tick already was infected before the blood meal or acquired the pathogen while feeding; not indicative of transstadial passage of pathogen[e]
Fully quantitative (numerator and denominator)	Pets (cats, dogs, and horses)	Systematic tick collection from a defined pet animal population	Tick encounter location difficult to interpret without travel and activity history for the time period when the tick encounter may have occurred	Not clear if the tick already was infected before the blood meal or acquired the pathogen while feeding; not indicative of transstadial passage of pathogen[e]
Fully quantitative (numerator and denominator)	Humans (crawling or attached ticks)	Systematic tick collection from a defined human population	Tick encounter location difficult to interpret without travel and activity history for the time period when the tick encounter may have occurred	Infection very likely indicative of transstadial passage of pathogen following previous infectious blood meal for both crawling and attached ticks[f]
Opportunistic; semi-quantitative (numerator only)	Environment	Opportunistically collected host-seeking ticks submitted by members of the public[a]	Fine-scale determination of tick encounter location possible if submission includes notes on collection location (e.g., in submitter's backyard)	Infection indicative of transstadial passage of pathogen following infectious blood meal[d]
Opportunistic; semi-quantitative (denominator only)	Wild animals	Opportunistic tick collection from road-killed animals[b]	Tick encounter location falling somewhere within the spatial activity range of the host species the tick was collected from	Not clear if the tick already was infected before the blood meal or acquired the pathogen while feeding; not indicative of transstadial passage of pathogen[e]
Opportunistic; semi-quantitative (numerator only)	Livestock (e.g., cattle, sheep, and goats)	Opportunistic tick collection from livestock via veterinary clinic networks during routine animal health activities[c]	Tick encounter location falling within readily defined host movement range, unless livestock were moved by vehicle during the time period when tick encounter may have occurred	Not clear if the tick already was infected before the blood meal or acquired the pathogen while feeding; not indicative of transstadial passage of pathogen[e]
Opportunistic; semi-quantitative (numerator only)	Pets (cats, dogs, and horses)	Opportunistic tick collection from pets by members of the public or via veterinary clinic networks during routine animal health activities[c]	Tick encounter location difficult to interpret without travel and activity history for the time period when the tick encounter may have occurred	Not clear if the tick already was infected before the blood meal or acquired the pathogen while feeding; not indicative of transstadial passage of pathogen[e]
Opportunistic; semi-quantitative (numerator only)	Humans (crawling or attached ticks)	Opportunistic tick collection via medical clinic networks during routine health activities; opportunistically collected ticks submitted by members of the public to tick identification/pathogen testing service programs[c]	Tick encounter location difficult to interpret without travel and activity history for the time period when the tick encounter may have occurred	Infection very likely indicative of transstadial passage of pathogen following previous infectious blood meal for both crawling and attached ticks[f]

[a] Numerator (number of collected ticks) can be quantified but there is no denominator due to lack of a systematic sampling design.

[b] Denominator for number of examined animals can be quantified but an unknown proportion of attached ticks may have already dislodged from road-killed carcasses before they were recovered and examined for ectoparasites, therefore the numerator for number of infesting ticks cannot be reliably quantified.

[c] Numerator (number of collected ticks) can be quantified but there is no denominator because the number of potential tick hosts from which ticks would have been recovered were the hosts infested is unknown.

[d] With the following exceptions: 1) infection of host-seeking larval ticks with a pathogen that can be passed transovarially from the female to her offspring; and 2) infection in ticks having taken only a partial blood meal and seeking a second host to take sufficient additional blood to be able to molt to the next life stage or lay eggs. Host-seeking nymphs or adults infected with a pathogen that can be passed transovarially from the female to her offspring represent another special case where infection is indicative of transstadial passage but not necessarily of a preceding infectious blood meal for the individual tested tick.

[e] Not all wild animal species, livestock species, or pet species serve as reservoirs for a given tick-borne pathogen; pathogen detection result should be interpreted bearing in mind the reservoir competency of the host animal for the pathogen in question.

[f] Humans are considered dead-end hosts for tick-borne pathogens.