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A citizen science approach to investigate the distribution, abundance, and pathogen infection of vector ticks through active surveillance

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ABSTRACT

Tick-borne disease poses a growing public health burden in the United States and understanding the patterns of presence and density of infected vector ticks is key to developing and implementing effective public health management strategies. Citizen science has emerged as a highly effective means to generate data sets on the geographical distribution of tick species. But to date, nearly all citizen science studies of ticks are 'passive surveillance' programs in which researchers accept reports of ticks, together with either physical specimens or digital images, found opportunistically on people, pets, and livestock from community members for species identification and in some cases also tick-borne pathogen detection. These studies are limited because data are not collected systematically, making comparisons among locations and over time challenging, and introducing considerable reporting bias. In this study, we engaged citizen scientists in 'active surveillance' of host-seeking ticks, training volunteers to actively collect ticks on their woodland properties in an emergent region of tick-borne disease in the state of Maine, USA. We developed volunteer recruitment strategies, materials to train volunteers in data collection methods, field data collection protocols based on techniques used by professional scientists, and a variety of incentives to promote volunteer retention and satisfaction with their experiences, and we communicated research findings to participants. A total of 125 volunteers in 2020 and 181 volunteers in 2021 collected 7,246 ticks in southern and coastal Maine, including the American dog tick (*Dermacentor variabilis*, 4,023 specimens), the blacklegged tick (*Ixodes scapularis*, 3,092 specimens), and the rabbit tick (*Haemaphysalis leporispalustris*, 102 specimens). We demonstrated the feasibility of citizen scientists collecting ticks using active surveillance methods and found that volunteers were motivated to participate largely by their interest in the scientific problem and a desire to learn about ticks on their properties.

1. Introduction

Arthropod-borne zoonotic diseases (i.e., those caused by pathogens associated with wildlife and transmitted to humans via the bite of an infected arthropod) constitute 30% of emerging infectious diseases worldwide (Jones et al., 2008), and recent decades have seen numerous vector-borne pathogens spread at unprecedented rates through susceptible human populations (Chala and Hamde 2021). The most important vector-borne disease agents in the United States include pathogenic bacteria, protozoa, and viruses transmitted by hard-bodied ticks (Acari: Ixodidae). Over the past decade, over 300,000 human cases of Lyme disease have been reported from the United States (Bisanzio et al., 2020; Gardner et al., 2020), which are assumed to represent a ten-fold underestimate of total cases (Kugeler et al., 2021; Schwartz et al., 2020), and numerous other tick-borne diseases are on the rise (Sonenshine, 2018; Rochlin and Toledo, 2020). The distribution of ticks and the pathogens they transmit can be heterogeneous across spatial scales (e.g., Wimberly et al., 2008; Machtinger et al., 2021) and understanding the patterns of density of infected vectors is key to developing and implementing effective public health management strategies.

Citizen science has emerged as a highly effective means to generate long-term data sets on the large-scale distribution of vector tick species

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(reviewed in Eisen and Eisen, 2021). Nearly all citizen science studies of ticks are 'passive surveillance' programs in which researchers accept reports, together with either physical specimens or digital images, of ticks found opportunistically on people, pets, and livestock from individuals including veterinarians, human healthcare providers, and residents for species identification and in some cases also tick-borne pathogen detection. Passive surveillance has proven a cost-effective strategy that may offer a sensitive indicator of tick occurrence in regions where geographic range expansion of ticks and their associated pathogens is ongoing and detection probabilities are low. For example, the long-running TickSpotters program at the University of Rhode Island Tick Encounter Resource Center has filled in gaps in the county-scale distribution of the blacklegged tick (*Ixodes scapularis*), the western blacklegged tick (*Ixodes pacificus*), and the lone star tick (*Amblyomma americanum*) through an online tick image submission system (Kopsco et al., 2021a), and a tick submission and identification program led for 24 years by the Maine Medical Center Research Institute documented the spread and establishment of the blacklegged tick in Maine (Elias et al., 2021). Public tick reporting programs also recently have been used to characterize tick phenology (Xu et al., 2016; Rounsville et al., 2021), investigate tick-human interactions (Fernandez et al., 2019), and build town-scale tick-borne disease forecasting models (Little et al., 2019).

Yet while passive surveillance data sets provide valuable insight in certain contexts, data are not collected systematically, making comparisons among locations and over time challenging, and introducing considerable reporting bias, e.g., in areas or during time periods where tick submission programs are advertised more heavily. Passive surveillance builds 'presence-only' data sets from which it cannot be inferred whether the apparent absence of ticks in locations reflects the true absence of species or lack of reporting (Eisen and Eisen, 2021), and people may encounter ticks not only in their yards or neighborhoods, but also outside their immediate area of residence (Fischhoff et al., 2019). Passive surveillance programs must try to obtain travel histories from tick submitters to accomplish any degree of geographic precision in data collection and consider how confident they are in submitters' classification of where ticks likely originated. Finally, species that do not commonly bite humans may easily be confused with important vector species in image-based tick identification systems. For example, *Ixodes cookei, Ixodes dentatus, Ixodes angustus*, and *Ixodes affinis* are morphologically similar to *I. scapularis*.

Understanding the drivers of fine-scale heterogeneity in tick abundance also demands a more rigorous data collection approach than the detection of tick presence offered by citizen science via passive surveillance. For example, 'active surveillance' studies, in which ticks are directly, systematically collected from the environment using standardized techniques and metrics (e.g., per unit area or per unit time), have revealed that forest management within stands (e.g., invasive plant removal, timber harvesting, and prescribed burns) can impact tick densities and infection prevalence (Stafford et al., 1998; Elias et al., 2006; Padgett et al., 2009; Williams et al., 2009; Conte et al., 2021). However, due to the high cost of labor associated with active surveillance, most of this research has been conducted on a small number of plots over short time scales, limiting the generalizability of findings across ecological contexts. Understanding impacts of forest management on tick distribution and abundance at spatial and temporal scales beyond the scope of what can be achieved by a typical small team of research scientists could potentially inform development of guidelines for landscape-based area-wide tick management, and we propose that citizen science may again provide an efficient and effective approach to accomplish this goal.

The Maine Forest Tick Survey was conceptualized as the first U.S.-based citizen science project using active tick surveillance, in which trained volunteers (private woodland landowners) follow a standardized protocol to collect and preserve ticks on their own properties for subsequent identification and pathogen detection by researchers. The focus of our project was to estimate abundance and infection prevalence with common tick-borne pathogens in the region of the blacklegged tick, an important vector species that transmits multiple pathogens to humans and animals in the eastern and midwestern U.S. (Fleshman et al., 2022), in these managed woodlands. Our study design offers the opportunity for more rigorous data collection than passive surveillance while educating volunteers about tick exposure risk on their woodlands through hands-on research participation and training in the scientific method. The goal of this paper is to discuss unique aspects of our study design and methods, including volunteer recruitment, training, and retention efforts, and data collection protocols. We also present, as descriptive data, highlights of our findings during an initial two-year study period, and qualitatively compare our tick distribution findings to publicly available data from a passive tick surveillance program in the state of Maine.

2. Materials and methods

2.1. Volunteer recruiting

This study was conducted under the University of Maine Institutional Review Board protocol #2019–06–07. We recruited volunteers through a press release and a project website (https://umaine.edu/foresttsicksurvey) during March and April of each of two study years (2020 and 2021). We also created social media accounts for the project on Facebook and Twitter and we asked outside organizations (e.g., Maine Woodland Owners, Maine Master Naturalists, and Maine Land Trust Network) to share information about the study with their members and followers. Interested potential volunteers filled out a brief pre-screening questionnaire on the project website and provided contact information and basic property characteristics, including property location, number of acres, and timber harvesting history, the latter of which is a long-term interest of our project that is not discussed extensively in this article. We used this information to select volunteers with diverse property management histories (i.e., property size and time since the most recent timber harvest) across a wide geographic area with relatively even coverage of the focal counties. The study area was confined to nine counties in southern and coastal Maine (Androscoggin, Cumberland, Hancock, Kennebec, Knox, Lincoln, Sagadahoc, Waldo, and York Counties) due to their high proportion of non-industrial private forest landownership (Fig. 1A; Maine Forest Service) and high incidence of Lyme disease (Fig. 1B; Maine Center for Disease Control). We accepted 125 volunteers who owned between 4 and 405 wooded hectares (10–1000 acres) during year 1 and 181 volunteers who owned between 2 and 405 wooded hectares (5–1000 acres) during year 2 (Fig. 1C). Forty-three volunteers participated in both years to control for the effect of interannual variation in tick population size.

2.2. Volunteer training

Volunteer training focused on data collection, reporting protocols, and tick safety. We trained new volunteers during a live 90-min webinar that we offered twice per year. The webinar introduction covered a brief history of citizen science, tick biology and ecology, and goals of the citizen science study. Project instructions included how to select an appropriate tick collection site, collect ticks using the 'drag sampling' active surveillance technique, identify selected invasive plant species, and fill out the data sheets and questionnaires. We concluded the webinar with a section on tick safety which included information about appropriate clothing for tick collections and how to conduct tick checks and removal. Volunteers were asked not to use repellents while completing tick collections on the chance that this might affect data collection. We encouraged participants to type their questions into the chat box during the training webinar. Volunteer questions either received an immediate chat response from the moderator or were flagged and answered aloud. Upon completion of the webinar, we sent each

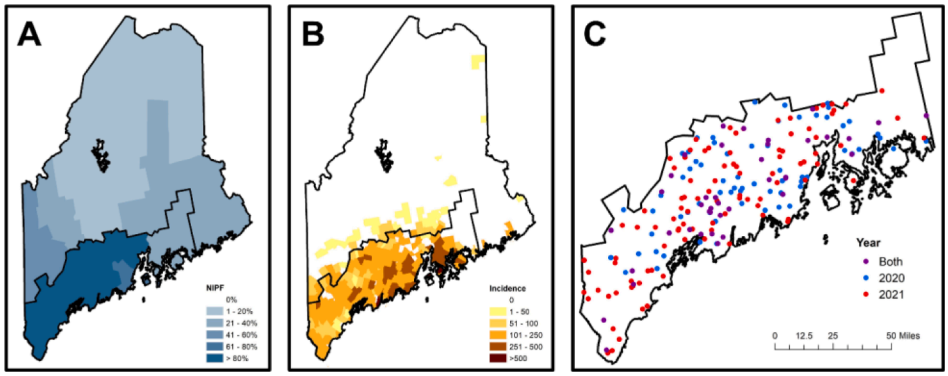

Fig. 1. Maps of (A) percent non-industrial private forest (NIPF) landownership in counties in Maine, USA, (B) five-year Lyme disease incidence per 100,000 people from 2017 to 2022, and (C) locations of Maine Forest Tick Survey volunteers' properties in 2020 and 2021. The bordered area indicates the counties considered as part of the study.

potential volunteer an email to confirm their participation. We recorded the webinar and made it available through a password-protected page on the project website for anyone who was unable to attend or who wished to review the information afterward. We also created a separate six-minute video that detailed how to select a site for sampling, drag for ticks, and fill out the data sheets.

2.3. Field data collection

Each participant was given a tick collecting kit (valued at $27) that included materials for collecting ticks, printed instructions, and data sheets (Fig. 2). We dropped off supplies to volunteers' homes in year 1 (due to COVID-19 social distancing restrictions) and used libraries as supply pick-up/drop-off locations in year 2. The kit contained tweezers to handle ticks, a magnifying card, four scintillation vials of 70% ethanol to store field-collected ticks, printed protocol sheets, and separate data sheets to fill out at each tick collection. Additionally, we supplied each volunteer with a 1 m^2 drag cloth made according to U.S. Centers for Disease Control and Prevention guidelines (https://www.cdc.gov/ticks/resources/TickSurveillance_Iscapularis-P.pdf). Drag cloths are used to collect host-seeking ticks by dragging the cloth over the top of leaf litter and low-growing vegetation (Falco and Fish, 1992). The drag cloths were constructed from untreated flannel with a waterproof core (90% Cotton Face and Back, 10% PVC Core, Joann Fabrics, Hudson, OH, USA); there is evidence that flannel captures more ticks, especially nymphs, than other materials (Simmons et al., 2021). For data management, each ethanol vial had a unique code printed in duplicate and placed inside and taped to the outside of the vial. Volunteers recorded their vial code for each collection as part of their data reporting. We created a tick identification card with dead blacklegged ticks (adults, nymphs, and larvae, though the latter were not a target life stage) to train volunteers to spot ticks. To create the card, dead ticks that had been preserved in ethanol were dried and taped onto an index card using transparent tape, and each life stage was labeled.

Volunteers collected ticks from their properties a total of three times during the month of July, with collections spaced roughly a week apart. We chose to collect data in July because this corresponds to the peak population size of nymphal blacklegged ticks in Maine (Conte et al., 2021; Elias et al., 2021; Rounsville et al., 2021; McBride et al., 2023). Blacklegged tick nymphs represent the species and life stage most likely to transmit pathogens to humans in Maine (Adams et al., 2015). Volunteers were instructed to collect ticks in predominantly deciduous habitats (Ginsberg et al., 2004; Lubelczyk et al., 2004) during dry weather conditions between 1000 and 1600 h by walking at a 'wedding march' pace while pulling a drag cloth over low-growing vegetation and fallen leaves. We asked volunteers to collect only adults and nymphs, as larvae are difficult and time-consuming to collect due to their small size and they rarely harbor pathogens. Volunteers walked in linear transects for 20 min, stopping once per minute for ease of volunteer effort to inspect and transfer any ticks from the drag cloth into the ethanol vial. Time spent searching for and removing the ticks was not included as part of the 20-min sampling period. After sampling, volunteers filled out their paper data sheets noting the time, date, and weather conditions of tick collections, and they later entered the data into an online Qualtrics® (Qualtrics, Provo, UT, USA) questionnaire to streamline data processing.

Due to well-documented associations between tick densities and presence of invasive plants at fine spatial scales (Elias et al., 2006; Williams et al., 2009; Williams and Ward, 2010), we also trained our volunteers to identify common invasive plants that occur in southern Maine during sampling. Target species included Japanese barberry (*Berberis thunbergii*), bush honeysuckle (Lonicera sp.), common buckthorn (*Rhamnus cathartica*), glossy buckthorn (Frangula alnus), and Asiatic bittersweet (Celastrus orbiculatus). We supplied online invasive plant identification guides in year 1 and created a portable invasive plant identification card in year 2 at the request of volunteers. While our findings regarding relationships between ticks and invasive plants are not presented in this article, our protocol is illustrative of the types of data collection that citizen scientists could learn to inform scientific

Fig. 2. Tick collecting supplies provided to each volunteer for the Maine Forest Tick Survey (left) and drag sampling tick collection technique (right).

research questions.

2.4. Tick processing and tick-borne pathogen analysis

After retrieving the tick specimens, we sorted all ticks by life stage, sex, and species using dichotomous keys (Kierans and Litwak, 1989; Egizi et al., 2019) and a Nikon SMZ 800 N stereo microscope (Nikon Instruments, Inc., Melville, NY, USA). To understand what other non-tick arthropod groups commonly are mistaken for ticks even by trained volunteers, any non-tick specimen submissions were sorted to order using reference images.

All blacklegged tick nymphs were individually sorted into microcentrifuge tubes and screened for *Borrelia burgdorferi* sensu lato (s.l.) (which includes *B. burgdorferi* sensu stricto, the primary causative agent of Lyme disease in the United States), *Anaplasma phagocytophilum* (human granulocytic anaplasmosis), and *Babesia microti* (human babesiosis). To disrupt the exoskeleton and expose internal tissues, nymphal ticks were disrupted using a bead beater. DNA was extracted and purified from tissues using Qiagen DNeasy Blood and Tissue Kit (QIAGEN, Valencia, CA, USA) and supplementary extraction protocol provided by the manufacturer. *Borrelia burgdorferi* s.l., *A. phagocytophilum, B. microti*, and ixodid DNA targets were detected using a qPCR quadruplex assay at the University of Maine Cooperative Extension Diagnostic and Research Laboratory (Orono, ME, USA) according to protocols described in Rounsville et al. (2021). Each PCR reaction was of 10μL reaction size containing 2μL of DNA template (extracted from ticks or control samples), 5μL of Bio-Rad (Hercules, CA, USA) iQ Multiplex Powermix and 3μL of premixed primers and probes. The qPCR reactions were completed on a Bio-Rad CFX 96 with a 3-min initial burn-in at 95 °C and annealing-extension of 40 cycles at 95 °C (15 s) and 60 °C (45 s). Samples were considered positive for a particular pathogen if DNA from the internal tick DNA control and pathogen of interest were amplified with a CQ (CT) value less than or equal to 35. To reduce the possibility of false-positive results for *B. microti*, a secondary SYBR green assay was used to confirm the presence of *B. microti* in samples testing positive in the multiplex (Rounsville et al., 2021).

2.5. Online questionnaires

Because we are interested in testing hypotheses related to tick exposure risk among forest landowners and impacts of forest management history on tick abundance and pathogen infection prevalence as an element of our ongoing research, each participant was asked to fill out four online questionnaires throughout the study concerning their properties and their attitudes and practices regarding ticks. The questionnaires were disseminated via Qualtrics® and each participant was emailed a personalized link to track completion. The first questionnaire, which volunteers completed before beginning data collection, included questions regarding land management and decision-making history, demographic information, and motivation for participating in citizen science. The three subsequent questionnaires each had a section for the volunteers to fill out information pertaining to their tick collection that week (i.e., weather conditions, presence of invasive plants, and any other notes they felt were relevant). The second survey asked detailed questions about the sampling area's forest vegetation (e.g., leaf litter presence, sunlight exposure, and tree species composition) and the volunteers' tick knowledge and experience. The third survey asked questions related to perceived efficacy and acceptability of tick management options (e.g., removing small mammal reservoir hosts of tick-borne pathogens, applying pesticides, and changing forest management practices). The final survey focused on participants' personal protective behaviors to prevent tick bites (e.g., conducting tick checks, wearing certain clothing, and applying insect repellent). Again, while this research is ongoing and our focus in this paper is on the citizen science methodology, our protocol demonstrates the extent of data collection that participants engaged in without volunteer fatigue significantly impacting retention.

2.6. Volunteer engagement and retention

We communicated regularly with volunteers to ensure they completed all tasks on time. We sent a questionnaire and a reminder of upcoming tasks to volunteers by email each week in July. In addition to the weekly emails in July, we sent two automatic reminders to each participant that had not completed their questionnaires in August. As an incentive to complete the study, we sent individualized reports to volunteers that listed the species and pathogen infection status of ticks they collected. We also created and distributed annual summary reports with overall project results including total number of ticks collected, pathogen prevalence by county, and correlations between certain management practices and tick densities. These reports were disseminated through the project website and press releases. One of the most requested suggestions during year 1 of the study was to incorporate a social element into the project. During year 2, we created a private Facebook group for our volunteers to talk with one another, share pictures and stories, and ask questions. The group was a popular addition in year 2, with over 50 posts and 200 comments during the three-week tick collection period.

3. Results

3.1. Study participants

We received 297 volunteer applications in year 1 and 214 in year 2, with a waitlist to participate in the study both years. Most potential volunteers heard about the project from print or online newspaper articles, followed by social media. Due to the constraints of our project budget, we accepted 125 volunteers in year 1 (86% of whom completed the study) and 181 in year 2 (84% of whom completed the study), including 43 repeat volunteers in year 2. Properties were evenly distributed across the study area (Fig. 1C). Most volunteers were highly educated and had an undergraduate or graduate degree (85% in year 1, and 79% in year 2). Volunteers ranged in age from 25 to 86 with a median age of 64 in year 1 and 56 in year 2, and overall, 52% of volunteers identified as women.

Volunteers reported numerous reasons for participating in this study, but their primary interest was in learning about ticks and tick-borne disease in the state and on their properties (Table 1). The top motivations that over 90% of participants identified to volunteer for the Maine Forest Tick Survey were "I want to learn more about ticks" and "I want to know about tick-related risks on my property." Participants also were interested in contributing to the scientific process. Overall, participants expressed a reasonably high degree of concern about exposure to ticks and tick-borne pathogens (65% rated their concern about Lyme disease on their property as being "moderately" to "extremely" concerned), and their personal experience with tick-borne disease was higher than the national average (20% indicated that they personally had been diagnosed with Lyme disease previously, and 96% indicated that someone they knew had been diagnosed).

3.2. Forest land use and management

Our volunteers owned wooded land for a variety of reasons, especially to protect nature or biological diversity, to enjoy beauty or scenery, to protect or improve wildlife resources, and for privacy (Table 2). Participants reported using their land for recreational activities, such as hiking/walking, skiing/snowshoeing, and hunting, on a daily or weekly basis, and expressed an overall lack of desire to modify their regular use of their land in response to tick-borne disease exposure risk (64% of volunteers indicated that they do not avoid areas on their property that may have ticks for fear of contracting Lyme disease). Seventy-two percent of volunteers reported ever having conducted a timber harvest

Table 1
Ten most important and least important self-reported reasons that study participants volunteered for the Maine Forest Tick Survey (2020 and 2021 combined).

Item	Agreement*,%			n
	Agree	Neutral	Disagree	
I want to learn more about ticks	95.0	5.0	0.0	222
I want to know about tick-related risks on my property	94.1	5.9	0.0	222
It is a good project to participate in	92.8	7.2	0.0	221
I want to contribute to the knowledge of this project	91.4	8.1	0.5	222
I want to contribute to tick research	90.5	9.0	0.5	222
I am happy to help	90.5	9.5	0.0	222
I am interested in ticks	88.3	11.7	0.0	222
I feel a strong connection with nature	87.3	12.7	0.0	221
I want to contribute to the well-being of others	87.3	12.2	0.5	221
I want to contribute to science	86.9	12.6	0.5	221
Volunteering is a good escape from Covid-19 stress	20.6	52.5	26.9	223
Volunteering makes me feel important	17.6	63.5	18.9	222
I regularly participant in citizen science projects	15.8	45.5	38.7	222
I want to advance my career	6.3	48.9	44.8	221
I have more free time than usual because of Covid-19	6.3	37.8	55.9	222
I am unable to do my regular activities due to Covid-19	6.3	32.7	61.0	223
Other people I know are participating	5.4	26.6	68.0	222
I want something to occupy my time during Covid-19	5.4	46.2	48.4	223
An organization I'm part of requested I help	3.2	22.6	74.2	221
I want to gain recognition and status	1.4	37.8	60.8	222

* Based on a 5-point Likert scale, where "Strongly Agree" and "Agree" were collapsed into "Agree" and "Strongly Disagree" and "Disagree" into "Disagree".

Table 2
Self-reported importance of reasons for owning wooded land among the Maine Forest Tick Survey participants (2020 and 2021 combined).

Item	Importance (1 = low, 5 = high),%					Mean	n
	1	2	3	4	5		
To protect nature or biological diversity	0.0	2.3	10.8	30.2	56.8	4.4	222
To enjoy beauty or scenery	0.5	3.2	7.8	32.9	55.7	4.4	219
To protect or improve wildlife resources	0.5	4.6	12.7	28.2	54.1	4.3	220
For privacy	3.6	3.6	14.0	25.8	52.9	4.2	221
For recreation, other than hunting	1.4	5.8	14.4	36.8	41.7	4.1	223
To protect water resources	2.7	9.1	17.7	31.4	39.1	4.0	220
To raise my family	15.7	10.2	9.7	27.3	37.0	3.6	216
To pass land on to my children or other heirs	16.4	17.4	24.2	15.5	26.5	3.2	219
For firewood	23.0	23.9	17.6	18.9	16.7	2.8	222
For land investment	19.3	23.4	25.7	19.3	12.4	2.8	218
For hunting	49.1	15.0	9.6	10.9	15.5	2.3	220
For nontimber products, e.g., berries, syrup	36.0	25.2	18.9	10.4	9.5	2.3	222
For timber products, e.g., logs, pulpwood	43.2	24.1	15.0	11.4	6.4	2.1	220

on their land during their ownership period while 38% reported the presence of invasive plants.

3.3. Ticks and pathogens

Volunteers collected 7246 total ticks over both years (excluding larvae) representing three different tick species (see Table 3 for a breakdown of numbers of nymphs and adults collected). Tick species collected over the lifetime of the project included the American dog tick (*Dermacentor variabilis*, 4023 specimens, all adults), the blacklegged tick (*I. scapularis*, 3092 specimens, predominantly nymphs), and the rabbit tick (*Haemaphysalis leporispalustris*, 102 specimens, all nymphs). Although we instructed volunteers to collect only adults and nymphs, volunteers also collected 1572 larvae; these were not identified to species. Volunteers collected significantly more adult and nymphal ticks in year 2 (5294 total ticks including 14.8 ± 2.0 SE blacklegged tick nymphs collected per property) compared to year 1 (1952 total ticks including 4.8 ± 0.8 SE blacklegged tick nymphs collected per property) ($T = 4.31$; df = 215; $P < 0.01$). Variance in tick counts among properties was high and generally exhibited a qualitatively similar county-scale spatial pattern to non-population-adjusted tick submissions to the University of Maine Cooperative Extension passive surveillance program (https://extension.umaine.edu/ticks/maine-tick-data/) over the same years (Fig. 3). Least squares regression showed a weak correlation between age of the collector and total number of ticks collected ($R^2 = 0.03$); older volunteers collected fewer ticks compared to younger volunteers ($F = 5.22$; df = 1, 184; $P = 0.02$).

We tested a total of 2566 nymphal blacklegged ticks for three tick-borne pathogens and found comparable infection prevalence during years 1 and 2 of the study (Table 4). The highest proportion of nymphs were infected with *B. burgdorferi* s.l. (25% across both years) followed by *A. phagocytophilum* (6.2%) and *B. microti* (5.8%).

3.4. Non-tick specimen submissions

Over both years, 895 non-tick specimens were submitted by volunteers (Table 4). In year 1, a total of 440 non-tick specimens were submitted, or 20% of total specimens submitted. In year 2, 455 non-tick specimens were submitted, accounting for 7.7% of total submissions. Most of these specimens were mites (Acariformes and Parasitiformes) and spiders (Araneae), and less common submissions included nymphal and adult true bugs (Hemiptera) and adult beetles (Coleoptera).

4. Discussion

The Maine Forest Tick Survey is the first large-scale study to demonstrate the feasibility of active tick surveillance by citizen scientists. This approach overcomes many limitations of the numerous 'passive' resident-submitted tick surveillance programs that currently operate in the U.S., particularly reporting bias due to awareness of the programs, the lack of 'true zeroes' in presence only data sets, and the inability to draw quantitative comparisons across regions due to lack of standardized collection effort (Eisen and Eisen, 2021). Although the focus of our study was the blacklegged tick and tick-borne pathogen exposure risk in managed forests and our target audience was private owners of small- to medium-sized woodlots, our methods could readily be extended to other research questions and social-ecological contexts. We also envision our methods being applicable to analysis of tick exposure risk in peridomestic habitats (Fischhoff et al., 2019), and more generally for public health vector surveillance across the landscape, including in regions where ticks and their associated pathogens are emerging and thus tick detection probabilities through drag sampling conducted by public health departments may be low. For example, during the second year of the Maine Forest Tick Survey, the New York State Department of Health and Cornell University launched the New York State Tick Blitz, another active surveillance citizen science program targeting detection of two invasive tick species in the Hudson Valley, the lone star tick and the Asian longhorned tick (*Haemaphysalis longicornis*). Key objectives of tick surveillance, such as estimating tick densities and characterizing tick phenology, are expensive and laborious to accomplish at more than a small number of sites (Eisen and Paddock, 2021), and time and effort cost of processing data also has been identified as a barrier to timely dissemination of surveillance data to partners and stakeholders (Mader et al., 2021). The Maine Forest Tick Survey was

Table 3
Abundance and pathogen infection prevalence of tick species collected by Maine Forest Tick Survey participants in 2020 and 2021. Pathogens detected in blacklegged ticks included *Borrelia burgdorferi* sensu lato (Bbsl), *Anaplasma phagocytophilum* (Ap), and *Babesia microti* (Bm).

Species	Life Stage	Count*		% Bbsl positive		% Ap positive		% Bm positive	
		2020	2021	2020	2021	2020	2021	2020	2021
Ixodes scapularis	Adult	292	234	–	–	–	–	–	–
	Nymph	459	2107	25.2	24.3	7.5	5.8	5.5	5.8
Dermacentor variabilis	Adult	1151	2872	–	–	–	–	–	–
Haemaphysalis leporispalustris	Nymph	32	70	–	–	–	–	–	–
Unidentified	Larvae	961	611	–	–	–	–	–	–

* Per 125 participants in 2020 and 181 participants in 2021.

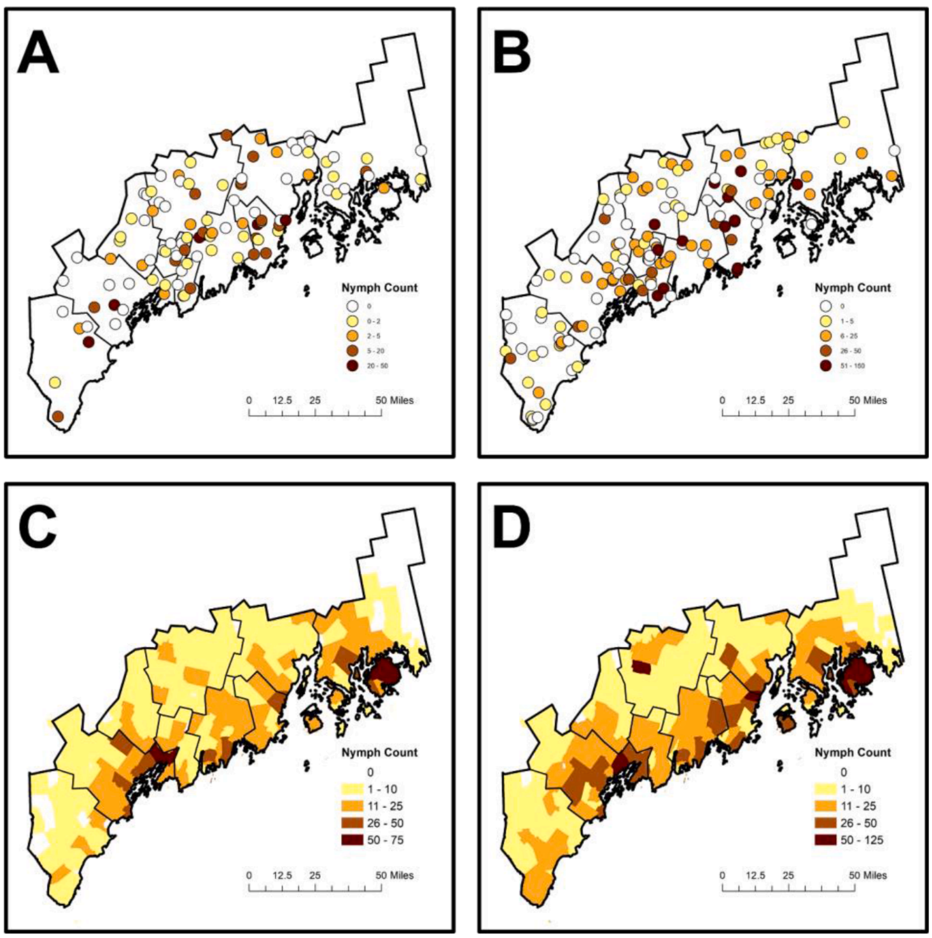

Fig. 3. Maps of tick counts per property in the Maine Forest Tick Survey in (A) 2020 and (B) 2021 compared to tick counts per town submitted to the University of Maine Cooperative Extension passive surveillance program in (C) 2020 and (D) 2021. Black lines indicate county boundaries.

Table 4
Abundance of non-tick specimens collected and submitted by Maine Forest Tick Survey participants in 2020 and 2021.

Group	Count		
	2020	2021	Total
Mites (Acariformes and Parasitiformes)	130	273	403
Araneae	132	49	181
Hemiptera	98	69	167
Coleoptera	37	22	59
Psocoptera	13	29	42
Other	30	13	43
Total	440	455	895

coordinated largely by one full-time scientific professional, and the reduced time and resource cost of surveillance (e.g., of travel to field sites) allowed for sharing of findings, including pathogen analysis, with volunteers and public audiences within eight months of data collection. As has been seen in citizen science active surveillance studies of other vector species (e.g., Palmer et al., 2017), our approach allowed for data collection at a large number of field sites and could be scalable to achieve coverage of different sized geographic areas. Our detection of tick-borne pathogen infection prevalence similar to the state's passive surveillance program (Rounsville et al., 2021) suggests that our results are well representative of statewide tick-borne pathogen prevalence.

Despite the labor- and time-intensive nature of the citizen science protocols, over 80% of accepted participants completed all aspects of the work, and several factors contributed to this high retention and completion rate. We found that most volunteers participated because they wanted to learn more about ticks, both broadly posed and specifically on their own properties. This is consistent with findings of prior research that suggest that one of the most common motivations to participate in citizen science is to learn more about topics of personal interest (Lotfian et al., 2020). The blacklegged tick was first detected in Maine in the 1980s and subsequently has spread throughout southern and coastal Maine (Rand et al., 2007; Elias et al., 2021), and we were able to capitalize on public interest in the dramatically increasing distribution and abundance of this species. Volunteers had multiple opportunities to learn more about ticks through training sessions, project reports, free tick-borne pathogen detection services (as of 2022, the passive surveillance program in the state of Maine costs a fee of $15/sample), and direct access to subject matter experts. Other community science programs have reported that volunteers are more likely to complete tasks when they are directly related to their motivations (Richter et al., 2021). The high completion rate in our study demonstrates that when volunteers' personal interests align with project goals, participants and study organizers can mutually benefit. Interruptions to participants' normal activities due to COVID-19 did not appear to be a significant driver of our study completion rate, although multiple studies have documented increases in citizen science participation during the pandemic, especially across virtual platforms such as eBird, iNaturalist (Sánchez-Clavijo et al., 2021), Zooniverse, and SciStarter (Drill et al., 2022).

We identified a few notable limitations that may vary in how challenging they would be to address in subsequent studies. A qualitative comparison of data collected via the Maine Forest Tick Survey versus passive surveillance revealed that passive surveillance achieved greater town-level coverage within the study area compared to citizen science surveillance. This, of course, comes at the cost of the passive data surveillance not being standardized (e.g., tick densities cannot be measured) and introduction of additional geographic variance if the exact locations of tick exposure are unknown. While we attempted to achieve relatively even county-level coverage of the study area in identifying study participants, future efforts may further improve coverage through more extensive advertising of the program in unrepresented towns. A related point is that the citizen science study design does not overcome the participation bias associated with awareness of the program and interest in the issue that also is inherent to passive surveillance. Almost all volunteers cited an interest in ticks on their own properties as an *a priori* motivation to participate, which may suggest that the self-selected volunteers live in areas with above average tick densities. However, during both years of the study, many participants did not collect any ticks, and depending on the surveillance objective (e.g., estimating prevalence of pathogens in tick populations or characterizing tick phenology), focusing data collection in high tick density areas might even be desirable. Finally, as has been seen in passive surveillance studies (Kopsco et al., 2021b), even trained volunteers submitted mis-identified non-tick specimens with some frequency (8–20% per year), although the factors that may have contributed to this (e.g., lack or misuse of training resources, mites and spiders easily mistaken for ticks, lack of time to identify arthropods before collecting in case they crawl off the drag cloth) are unknown.

Although our program educated participants about ticks and tick-borne pathogens, we also lacked a mechanism for volunteers to participate directly in development of research questions, study design, and data analysis. Citizen science research has the potential to teach non-scientists about scientific methods and increase their scientific literacy (Lusse et al., 2022). Volunteers in our study expressed interest in "contributing to science", and indeed, other studies have successfully included their volunteers in the creation of their projects. For example, the Monarch Larvae Monitoring Project (Kountoupes and Oberhauser, 2008) and the Invasive Mosquito Project (Thackrah et al., 2016) provide volunteers opportunities to develop their own research questions and tools to conduct their own analyses. Community scientists engaged in participatory research may see themselves as the bridge between professional scientists and community members by providing feedback on research methods and reports (Damiani et al., 2001). This highlights the valuable role volunteers can play to improve community science during all phases of the project from planning to result dissemination. Additionally, volunteer retention and knowledge gains may be improved by involving volunteers in the creation of the study design, research questions, and goals of the project. We recommend that future studies that use active surveillance of ticks engage community stakeholders more deeply in the identification of research problems.

5. Conclusions

In this study, we engaged citizen scientists in collection of host-seeking ticks on their woodland properties in an emergent region for tick-borne disease. As part of the initial two-year performance period of this program, we developed volunteer recruiting strategies, materials and webinars to train volunteers in data collection methods, field data collection protocols based on techniques used by professional scientists, a workflow for processing thousands of citizen-submitted tick specimens and communicating research findings to participants, and a variety of incentives to promote volunteer retention and satisfaction with their experiences. We demonstrated the feasibility of citizen scientists collecting ticks using active surveillance methods in which participants systematically searched for ticks, building upon dozens of studies that previously have engaged residents, doctors, and veterinarians in passive surveillance, in which individuals submit ticks encountered passively in the environment to researchers. We found that volunteers were motivated to participate largely by their interest in the scientific problem and a desire to learn more about ticks on their properties and in their communities. Future research efforts will seek to respond to participants' expressed desire to learn about the scientific process by involving volunteers in the development of key research questions.

Author statement

E.S.B., A.M.G., J.E.L., and C.C.S. conceptualized research questions and designed the study; E.S.B. and M.G.G. collected and curated data; A.M.G., J.E.L., and C.C.S. acquired funding; A.M.G. supervised the execution of the study; E.S.B. and A.M.G. prepared the first draft of the manuscript; and all authors contributed to reviewing and editing the manuscript.

Declaration of Competing Interests

The authors declare no competing interests.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ttbdis.2023.102144.

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