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Impact of Unexplored Data Sources on the Historical Distribution of Three Vector Tick Species in Illinois

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Abstract

We updated the Illinois historical (1905–December 2017) distribution and status (not reported, reported or established) maps for *Amblyomma americanum* (L.) (Acari: Ixodidae), *Dermacentor variabilis* (Say) (Acari: Ixodidae), and *Ixodes scapularis* (Say) (Acari: Ixodidae) by compiling publicly available, previously unexplored or newly identified published and unpublished data (untapped data). Primary data sources offered specific tick-level information, followed by secondary and tertiary data sources. For *A. americanum, D. variabilis*, and *I. scapularis,* primary data contributed to 90% (4,045/4,482), 80% (2,124/2,640), and 32% (3,490/10,898) tick records vs 10%, 20%, and 68%, respectively from secondary data; primary data updated status in 95% (62/65), 94% (51/54) and in 90% (9/10) of the updated counties for each of these tick species; by 1985 there were tick records in 6%, 68%, and 0% of the counties, compared to 20%, 72%, and 58% by 2004, and 77%, 96%, and 75% of the counties by 2017, respectively for *A. americanum*, *D. variabilis*, and *I. scapularis*. We document the loss of tick records due to unidentified, not cataloged tick collections, unidentified ticks in tick collections, unpublished data or manuscripts without specific county location, and tick-level information, to determine distribution and status. In light of the increase in tick-borne illnesses, updates in historical distributions and status maps help researchers and health officials to identify risk areas for a tick encounter and suggest targeted areas for public outreach and surveillance efforts for ticks and tick-borne diseases. There is a need for a systematic, national vector surveillance program to support research and public health responses to tick expansions and tick-borne diseases.

Key Words: tick, distribution, establishment, surveillance, Illinois

Research and published efforts have not identified or used all the historical information on vector ticks (Acari: Ixodidae) in Illinois to update temporal and spatial distribution and status maps of the three dominant tick vectors of public health importance in Illinois: the lone star tick, *Amblyomma americanum*; the American dog tick, *Dermacentor variabilis*; and the blacklegged or deer tick, *Ixodes scapularis* (CDC 2018).

Across the United States and Illinois, the geographic distributions of these three species have expanded in recent decades (Bouseman et al. 1990, Dennis et al. 1998, Rydzewski et al. 2012, Eisen et al. 2016, Nieto et al. 2018). Based on climate models, continued range expansion is predicted for *D. variabilis* (Minigan et al. 2018), which is assumed to be widespread in Illinois (CDC 2019b). *Amblyomma americanum* has expanded its range northward into the upper

Midwest, including Illinois (Monzón et al. 2016). *Ixodes scapularis* has spread south into Illinois from Wisconsin since the late 1980s, and likely from the east since the late 1990s (Eisen et al. 2016).

Human diseases caused by tick-borne pathogens have increased globally in recent decades (De la Fuente et al. 2008, Dantas-Torres et al. 2012). Lyme disease is the most common tick-borne illness in Illinois and the rest of the United States (Herrmann et al. 2014). Other frequently diagnosed tick-borne illnesses in Illinois residents include Spotted Fever Rickettsioses, Ehrlichiosis, Anaplasmosis, and Tularemia (IDPH 2018a).

Tick hosts such as white-tailed deer (*Odocoileus virginianus*) (Cortinas et al. 2006), small mammals, and birds (Hamer et al. 2012) are responsible for the movement of ticks (Sotala et al. 1973, Anderson et al. 1984, Lantos et al. 2017). Host movements vary with year and season, affecting tick expansion and distribution in the landscape (Gill et al. 2001, Allan et al. 2010).

Tick survival depends on habitat characteristics and weather (Kitron et al. 1991, Guerra et al. 2002, Schulze et al. 2009, Gilliam et al. 2018). Ticks rely on temperature to regulate rates of development and on humidity to regulate survival. A tick's ability to capture water from the atmosphere is modulated by remaining in vegetation closer to the ground to conquer periods of low relative humidity (Estrada-Peña and de la Fuente 2014). Habitat suitability models predict areas suitable for the establishment of *I. scapularis* across Illinois (Brownstein et al. 2003, Cortinas et al. 2006, Hahn et al. 2016) and should take into account weather, habitat and landscape characteristics.

There are spatial distribution maps of ticks with county-level information using active and passive surveillance published for Oklahoma (Barrett et al. 2015, Mitcham et al. 2017), Nebraska (Cortinas et al. 2014), and Iowa (Oliver et al. 2017). National spatial distribution maps, for *I. scapularis* (Dennis et al. 1998, James et al. 2015, Eisen et al. 2016, Nieto et al. 2018), *A. americanum* (Springer et al. 2014), and *D. variabilis* (James et al. 2015, Nieto et al. 2018) highlighted the status (established, reported, or not reported) for counties with available records. Existing distribution maps of tick vectors use heterogeneous data sources such as peer-reviewed literature, passive and active surveillance, entomological collections, and databases available for public access. We will focus on evaluating the impact of previously unexplored newly identified published and unpublished data (untapped data) on the historical distribution of three dominant tick vectors of public health importance in Illinois, *A. americanum, D. variabilis* and *I. scapularis*. Our objectives are to 1) compare published publicly available statewide distribution data from national distribution maps of *A. americanum, D. variabilis I. scapularis*, with previously unexplored, newly identified published and unpublished (untapped data) data sources; 2) update county-level distribution maps for the three main vector ticks in Illinois; 3) identify counties in Illinois in need of additional tick surveillance; and 4) illustrate the impact of untapped data on the historical tick distribution maps of these ticks in Illinois.

Materials and Methods

We collected, extracted, and compiled tick collection data for the three main tick vector species in all counties in Illinois: *A. americanum*, *D. variabilis*, and *I. scapularis* (previously *I. dammini*) expanding from 1905 through 31 December 2017. We collected data from peer-reviewed manuscripts, researchers, and tick or entomological collections that were either publicly available; or unreported to public collection databases. Entomologists and tick researchers identified old specimens from their collections and accessioned the data for this work.

For the identification and inclusion of data from manuscripts we conducted literature searches using Scopus (Elsevier.com), PubMed and Web of Science (Thomas Reuters, NY) with the following keywords: (tick* AND 'Amblyomma americanum' OR 'Lone star tick' OR 'Dermacentor variabilis' OR 'American dog tick' OR 'wood tick' OR 'Ixodes scapularis' OR 'deer tick' OR 'blacklegged tick') AND 'Illinois'. We screened for and removed duplicate manuscripts and tick records. We selected manuscripts based on the inclusion criteria (detailed below), downloaded, read, and assessed the complete text of the manuscripts for eligibility. We included all those manuscripts with specific Illinois county-tick data that provided specific tick numbers, or that allowed for the determination of a minimum number of ticks by species in that county within a year or a range of years.

We complemented this effort with a snowball technique and examined the referenced materials of the selected manuscripts as in Springer et al. (2014) to maximize the records evaluated; this leads to the inclusion of additional manuscripts.

The inclusion criteria comprised peer-reviewed manuscripts published before December 2017 who provided specific information on one of the three focal tick species, including county-specific tick data and year or range of years of tick collection. If more than one paper by the same author(s) utilized the same data, we selected the earliest manuscript as our data source. If we identified a dataset created and cited by one researcher as utilized in a manuscript written by a different researcher, we selected the original publication of the data as our data source.

Thirty-one papers met our criteria and were used to map tick occurrences (Figs. 1 and 2) and to summarize the available information obtained from the data sources (Tables 1–3). However, we included manuscripts with national tick distribution data and maps published before 1 August 2018. The information from these national distribution manuscripts (Dennis et al. 1998, Springer et al. 2014, James et al. 2015, Eisen et al. 2016, Nieto et al. 2018) contained information for all the counties in the state of Illinois; we used the Illinois data from these national distribution manuscripts to develop our baseline or 'original' statewide distribution and status for *A. americanum*, *D. variabilis,* and *I. scapularis*. We extracted data from the remaining manuscripts to build the dataset used to compare with the baseline information, and updated the distribution and status of *A. americanum*, *D. variabilis*, and *I. scapularis* in Illinois.

We expanded our data collection by contacting lead researchers from the 26 peer-reviewed publications identified. We excluded researchers with ticks from avian hosts to minimize tick data from neighboring counties or states, and the five national tick distribution papers informing our baseline. We included researchers whose manuscripts suggested that there was tick-level data for counties where our baseline information was not established.

We requested access to these researchers' tick-level collection data for all counties available, if they were in a position to share data and if the data was available or could be made available at the time of this work. We expanded data gathering efforts for all counties in Illinois by using the United States National Tick Collection (USNTC) and the 'TickReport' a Tick-borne Diseases Passive Surveillance (https://www.tickreport.com/) program. We also used the state of Illinois Department of Public Health (IDPH) data, which collects data across all the counties in Illinois.

Based on personal communications during past and current collaborations, we used our existing knowledge and contacted known sources of tick-level data and collections that were not publically available at the time of this work. This included contacting local officials in Kendall County Health Department (KCHD) and the Forest Preserve District of DuPage County (FPDDC), both known to have

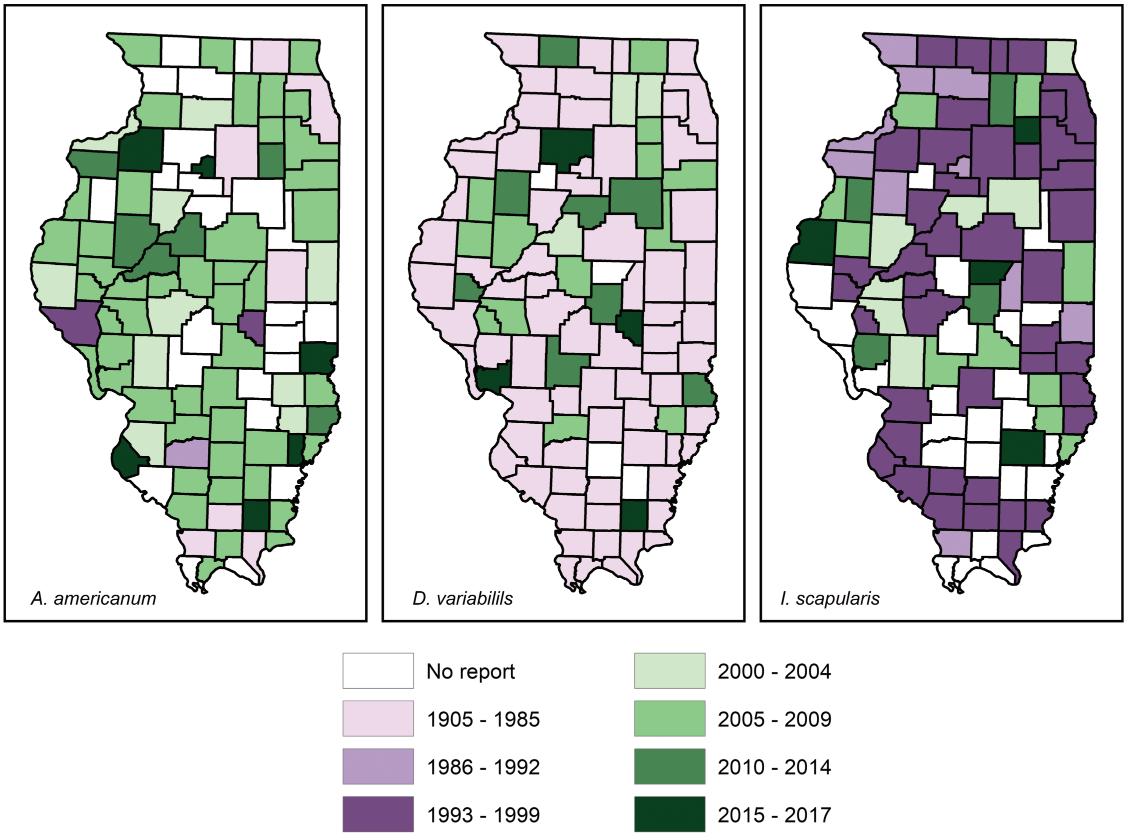
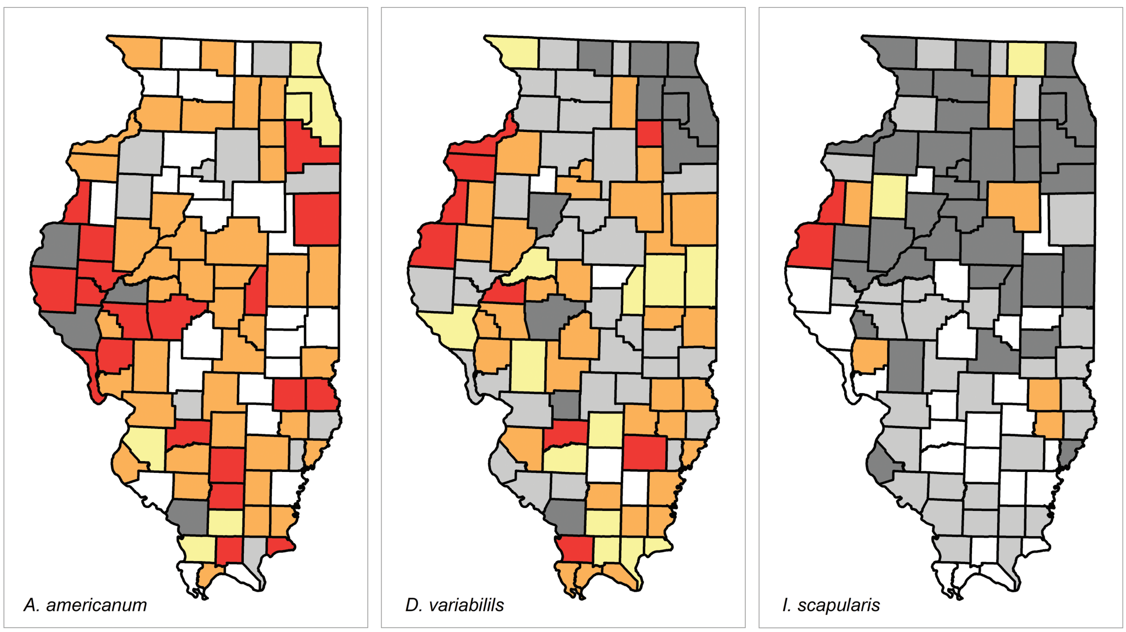
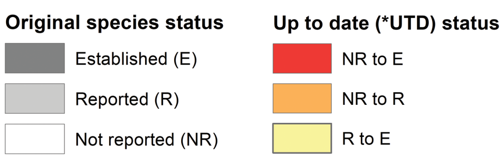


Fig. 1. First reports of three common vector ticks in Illinois from 1905 to 2017.





	A. americanum			D. variabilis			I. scapularis		
Status	Orig	UTD	**Total**	Orig	UTD	**Total**	Orig	UTD	**Total**
E	4	25	**29**	11	22	**33**	36	4	**40**
R	10	40	**50**	33	32	**65**	31	6	**37**
NR	23			4			25		

Fig. 2. Snapshot of vector tick distribution. Colored counties in red, orange, and yellow indicate updated status as of 31 December 2017. Original species status determined by five summary papers is in gray or white. We changed the grayscale to red, orange, or yellow depending on specific status update. *UTD status= updated status from this work.

Table 1. Primary data sources providing 'raw', non-aggregated specific tick-level data with collection location for *Amblyomma americanum, Dermacentor variabilis* and *Ixodes scapularis*

Primary data source[a]	No. of counties		Species identified (No.)	Year(s) of data collection[b]	Collection method	Host
	Total	By species				
INHS 2018	69	6	*Amblyomma americanum* (11)	1905…1999	Unknown	Unknown
		66	*Dermacentor variabilis* (726)			
		3	*Ixodes scapularis* (122)			
USNTC 2019	40	3	*Amblyomma americanum* (6)	1909…2001	Drag, Voluntary submission	Mammal
		39	*Dermacentor variabilis* (216)			
		3	*Ixodes scapularis* (36)			
Kitron et al. 1991[c]	1	1	*Ixodes scapularis* (1,000)	1990	Drag, field trap	Small mammal
FPDDC	1	1	*Amblyomma americanum* (3)	2003…2016	Drag, Voluntary submission	Unknown
		1	*Dermacentor variabilis* (46)			
		1	*Ixodes scapularis* (1064)			
IDPH	76	61	*Amblyomma americanum* (345)	2004…2017	Voluntary submission	Unknown
		41	*Dermacentor variabilis* (368)			
		38	*Ixodes scapularis* (223)			
J. Nelson	3	1	*Dermacentor variabilis* (4)	2005…2007	Drag	—
		3	*Ixodes scapularis* (83)			
Rydzewski et al. 2012[c]	5	5	*Dermacentor variabilis* (414)	2005…2009	Drag, field trap	Small mammal
		3	*Ixodes scapularis* (602)			
N. Mateus-Pinilla	42	24	*Amblyomma americanum* (870)	2007…2009	Drag, field trap, Voluntary submission	Human, dog, medium mammal
		28	*Dermacentor variabilis* (211)			
		8	*Ixodes scapularis* (150)			
TickReport 2019	35	15	*Amblyomma americanum* (28)	2008…2017	Voluntary submission	Human, dog
		20	*Dermacentor variabilis* (103)			
		15	*Ixodes scapularis* (110)			
Gilliam et al. 2018[c]	1	1	*Amblyomma americanum* (2,782)	2015…2016	Drag	—
		1	*Dermacentor variabilis* (24)			
		1	*Ixodes scapularis* (50)			
KCHD	1	1	*Dermacentor variabilis* (12)	2016…2017	Drag	—
		1	*Ixodes scapularis* (50)			

A single tick record included species, sex, life stage, collection method, host, county and year of collection (often month and day). Primary data sources found the three life stages, (adult, larva, and nymph) except for KCHD who only found adults and Kitron et al. 1991 who only found larvae.

[a]Tick specimens were provided by the public, Illinois Department of Natural Resources (IDNR) biologists, hunters, fellow scientists, Illinois Department of Public Health (IDPH; Curt Colwell specimen identification log 2017, unpublished data), US National Tick Collection (USNTC 2019), Kendall County Health Department (KCHD 2016, unpublished data), Forest Preserve District of DuPage County (FPDDC 2017, unpublished data), TickReport (2019), and Illinois Natural History Survey (INHS 2018) J. Nelson 2009, unpublished data; N. Mateus-Pinilla 2010, unpublished data.

[b]Dots between years indicate that the data sources provided specific collection dates within the year span.

[c]Data were published, but we received the primary data from the researcher and did not extract information from their manuscripts.

conducted independent tick dragging and data collection efforts prior to 2017; and, we and requested a special effort to identify, accession, update and share their data with us. Similarly, we contacted the Illinois Natural History Survey (INHS)—Insect Collection and requested their effort to identify and catalog tick specimens known (based on personal communications) with a collection date in Illinois before 31 December 2017, not yet identified. Furthermore, we identified the ticks from an existing historical collection effort belonging to one of the corresponding authors in this study and included that information in this work.

We separated data sources into primary, secondary, and tertiary categories based on the level of detail available from each source. We developed and followed decision rules to classify all the data sources into one of these three categories of data. Primary data exist as raw data at the individual tick-level originating from researchers and tick collections (not extracted from the published literature). Primary data required no interpretation to estimate the number of ticks and a tick status. They provided specific species, location for each tick collected, number of ticks, year and generally included life stage, sex, collection method, and host (Table 1).

We extracted secondary data from the text, figures, and maps of peer-reviewed manuscripts. These sources provided tick species, aggregated total number of ticks, county locations, approximate date of collection, or a range of 10 or fewer year(s) (Table 2), but we could not consistently determine the life stage for a single tick. Tertiary data sources included data from publications with established or reported species status by county but sometimes lacked specific year of tick collection or tick numbers (Table 3). If the data source did not provide the collection date, we used the year of publication as the collection date. Some tertiary data sources only provided enough information to determine the county of tick collection or to estimate a minimum number of ticks per county. For example, if the manuscript reported '*…adult and nymph I. scapularis were removed from 49 infested deer…*' we assumed a minimum of 49 *I. scapularis*, although we did not have the exact number of adults or nymphs; we interpreted the words '*infested deer*' as at least one tick per deer. If the data source did not provide specific tick information to help us characterize a tick species as established in a county (based on Dennis et al. 1998, and Eisen et al. 2016), but gave at least county and species information, we classified the county as reported.

Table 2. Summary of secondary data sources providing aaggregated numbers of ticks (*Amblyomma americanum, Dermacentor variabilis, and Ixodes scapularis)* for a county at an approximate date of collection or range of collection years

Secondary data source	No. of counties	No. of Ticks	Species identified	Year(s) of data collection[a]	Collection method	Host
Montgomery and Hawkins 1967	2	5	*Amblyomma americanum*	1964–1967	Field trap	Deer
	1	73	*Dermacentor variabilis*			
Nelson et al. 1984	1	226	*Amblyomma americanum*	1980–1983	Field trap	Deer
	1	11	*Dermacentor variabilis*			
Siegel et al. 1991	1	562	*Ixodes scapularis*	1989	Drag	—
Mannelli et al. 1993	1	1,399	*Ixodes scapularis*	1991	Mist net, field trap	Avian species, medium mammal
Slajchert et al. 1997	1	138	*Ixodes scapularis*	1993	Field trap	Small mammal
Chapman and Siegle 2000	1	68	*Amblyomma americanum*	1999–2000	Tick Suit, flag	—
	1	167	*Dermacentor variabilis*			
Bestudik 2006	1	2	*Ixodes scapularis*	2003–2004	Unknown	Unknown
Cortinas and Kitron 2006	17	3,789	*Ixodes scapularis*	1998–2003	Hunter-killed deer	Deer
Jobe et al. 2006	2	127	*Ixodes scapularis*	2005	Flag	—
Jobe et al. 2007	2	172	*Ixodes scapularis*	2006–2007	Drag	—
Rydzewski et al. 2011	1	1,009	*Ixodes scapularis*	2005–2009	Field trap	Small mammal
Hamer et al. 2012	1	28	*Ixodes scapularis*	2005–2010	Mist net	Avian species
Schneider et al. 2015	2	23	*Ixodes scapularis*	2012	Mist net, drag	Avian species
Zieman et al. 2017	1	117	*Amblyomma americanum*	2014	Field trap	Bobcat
	1	101	*Dermacentor variabilis*			
Nieto et al. 2018	11	21	*Amblyomma americanum*	2016–2017	Voluntary submission	Human, dog, other mammals
	33	164	*Dermacentor variabilis*			
	19	159	*Ixodes scapularis*			

These sources provided tick species, aggregated total number of ticks, county locations, and an approximate date of collection, or a range of 10 or fewer year(s) of collection. From a single source we could not consistently determine the life stages of the ticks or the exact year of collection.

[a]The data sources provided aggregate data between those years.

We established the following guidelines to maintain consistency while extracting secondary or tertiary data and converting them to discreet dates or locations. We chose the last year in a range of years reported as the actual 'year of the report or establishment'. We considered a tick species established if the aggregate number of ticks provided information for a range of years in a county but, we required the minimum number of ticks to be six times the total number of collection years in the year range. For example, for ticks (of the same species found in the same location) collected from 2003 to 2006, at least 24 ticks (four collection years multiplied by six) indicated the species was established. We screened the data for duplicates by comparing records for identical collector names, curators, collection dates, species, and county. We removed duplicate records from the dataset if a single person's records were found in two different data sources and removed records with the least amount of detail. If the data were very similar, but it was unclear that the tick collector was the same, we assumed that they were not duplicates and kept all records. Some data sources provided only a region, e.g., 'Chicagoland', instead of a county location. Without the number of ticks or county information, we could not determine or estimate the ticks found in a county and, therefore we did not include these sources in this work. These data sources did not pass out selection criteria to enter this study.

To depict spatial and temporal first reports and vector distribution status, we used ArcGIS 10.6 (ESRI, Redlands, CA) to map the first year of observation, or 'first report' (Fig. 1), and status (NR, R, or E) of *A. americanum*, *D. variabilis*, and *I. scapularis*. We followed the criteria used by Dennis et al. (1998) and Eisen et al. (2016), and if we collected two or more life stages or six or more individual ticks in a given county within the same year, we considered the tick species as established (E). If we found at least one tick species, we classified it as reported (R); if we did not detect tick records in a county, we recorded it as not reported (NR). Once a tick species was 'reported' in a county, it remained 'reported' unless new information became available, indicating a change to 'established'. Once a tick species was 'established', the status did not change regardless of new data.

We summarized the data by species, year collected, county, and life stage (when available) to determine the occurrence and species status (E, R, or NR). We defined and mapped our original baseline status (R or E) of a tick species using the information from all the national distribution manuscripts and represented this baseline knowledge in grayscale (Fig. 2). We used our baseline or 'original' distribution data and compared it with the tick distribution information gained from the primary, secondary, and tertiary data. We symbolized the updated status by county in red, orange, and yellow. The updated status red indicated a change from NR to E, in orange for NR to R, and in yellow for R to E (Fig. 2). Counties not updated from this work remained in grayscale.

In order to create a temporal visualization of tick-borne disease trends in Illinois from 1990 to 2017 (Fig. 3), we used data from the CDC's National Notifiable Infectious Diseases Surveillance System (CDC 2018), from the Illinois Department of Public Health (IDPH 2018a), and the tick-borne disease data from the CDC Morbidity and Mortality Weekly Reports (Adams et al. 2016, 2017). From all these sources, we extracted data on the most common five tick-borne diseases (Lyme disease, Ehrlichiosis, Anaplasmosis, Tularemia, and Spotted Fever Group Rickettsioses (SFGRs) associated with pathogens and transmitted by *A. americanum, D. variabilis*, and *I. scapularis* in Illinois.

Table 3. Aggregated data provided by tertiary data sources

Tertiary data source	No. of counties	No. of ticks[a]	Species identified	Year(s) of data collection[b]	Collection method	Host
Stannard and Pietscht 1958	1	4+	*Dermacentor variabilis*	1951–1954	Field trap	Medium mammal
Bouseman et al. 1990	1	72+	*Dermacentor variabilis*	1987–1988	Drag, hunter-killed deer	Deer
	9	9+	*Ixodes scapularis*			
Nelson et al. 1991	2	204	*Ixodes scapularis*	(1991)[c]	Drag	—
Kitron et al. 1992	1	100+	*Ixodes scapularis*	1988–1989	Hunter-killed deer	Deer
Lepitzki et al. 1992	1	8+	*Amblyomma americanum*	1983–1984	Field trap	Rabbit
Dennis et al. 1998	35	NA	*Ixodes scapularis*	1907–1996	Various	Unknown
Jones and Kitron 2000	1	100+	*Ixodes scapularis*	1990–1997	Drag, field trap	Small mammal
Cortinas et al. 2002	16	16+	*Ixodes scapularis*	1998–2000	Various	Deer, small mammal
Guerra et al. 2002	6	NA	*Ixodes scapularis*	1996–1998	Drag, field trap	Small mammal
Yoder and Benoit 2003	1	NA	*Amblyomma americanum*	1999–2002	Unknown	Unknown
Springer et al. 2014	11	21+	*Amblyomma americanum*	1930s–2009	Various	Unknown
James et al. 2015	33	NA	*Dermacentor variabilis*	1998–2011	Unknown	Unknown
Eisen et al. 2016	29	NA	*Ixodes scapularis*	1907–2015	Various	Unknown

[a]NA= the source does not provide exact tick numbers. A '+' indicates that the sources suggested a minimum number of ticks; for example, '…ten deer were infested…', so there were at least 10 ticks.

[b]The data sources provided aggregate data between those years.

[c]We used the year of publication to specify a relative year of collection when none was given.

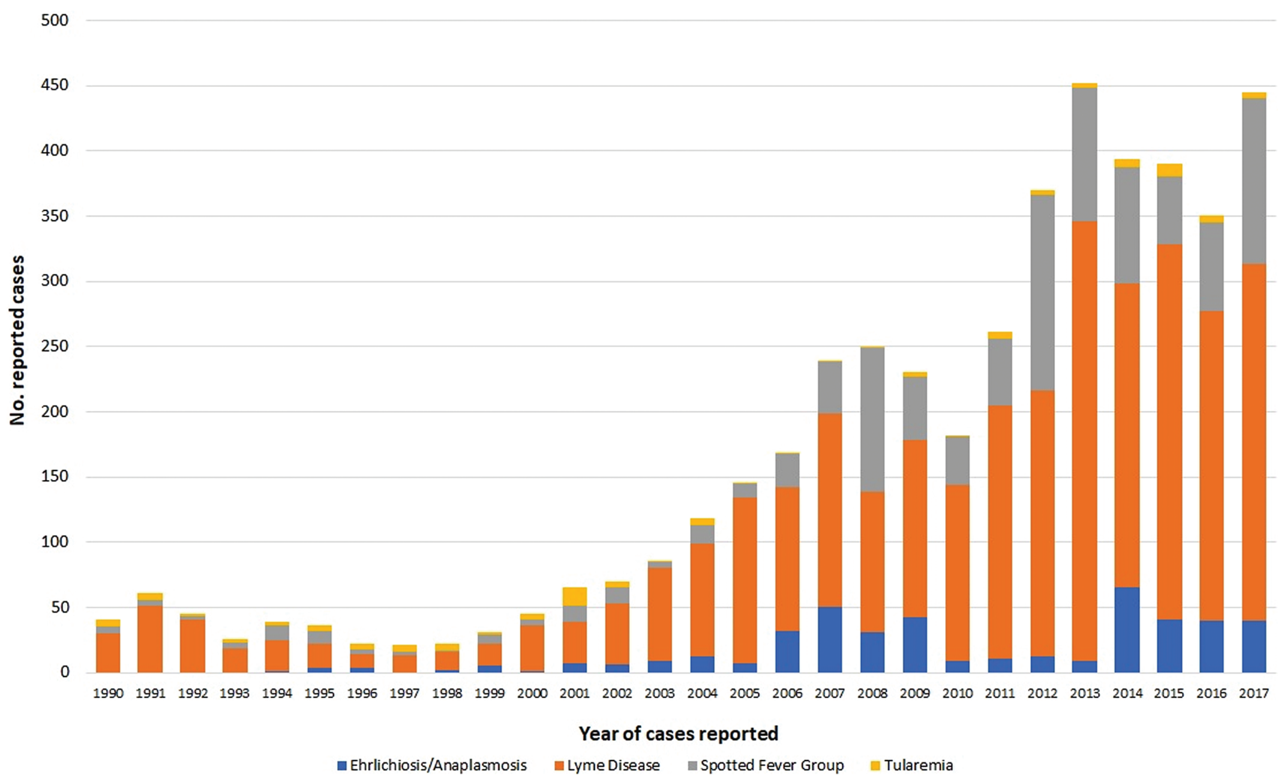


Fig. 3. Tick-borne disease trends in Illinois, 1990–2017, based on IDPH data.

Results

We updated the year range of 'first report' (Fig. 1) and provided the distribution maps and the status no report (NR), reported (R) or established (E) at the county level (Fig. 2) for the three main vector tick species in Illinois *A. americanum*, *D. variabilis*, and *I. scapularis*.

We identified 18,020 tick records (Supp Table S1 [online only]) collected from 39 data sources, including 30 published references from 1905 to 2017 and one national distribution manuscript published in July 2018. We found at least one tick record for one of the targeted tick species in 101 of the 102 counties in Illinois. Stark County was the only county without tick reports.

The distribution of *D. variabilis* was documented in 70 counties in Illinois from first reports before 1985 (Fig. 1) in contrast to reports in seven counties for *A. americanum* and no reports for *I. scapularis*. Fourteen years later (by the end of 1999), there were no additional counties with reports for *D. variabilis* although, there were first reports in 10 counties for *A. americanum* and 52 counties for *I. scapularis*. By the end of 2009, there were reports in 67, 86, and 69 counties for *A. americanum, D. variabilis* and *I. scapularis,* respectively. By the end of December 2017, there were tick reports in 79, 98, and 77 counties for *A. americanum, D. variabilis,* and *I. scapularis,* respectively. Based on primary, secondary and tertiary information we identified the total number of counties with NR, R or E status as follows: for *A. americanum* (NR = 23, R = 50, E = 29); for *D. variabilis* (NR = 4, R = 65, E = 33) and for *I. scapularis* (NR = 25, R = 37, E = 40) (Fig. 2, Supp Table S1 [online only]).

By using previously unexplored, newly identified published and unpublished data (untapped data sources), we updated the status in 65, 54, and 10 counties for *A. americanum, D. variabilis*, and *I. scapularis* respectively. The number of counties with status updates for *A. americanum* was 40 from (NR to R), 19 from (NR to E) and six from (R to E); for *D. variabilis* they were 33 from (NR to R), nine from (NR to E) and 12 from (R to E); and for *I. scapularis* they were six from (NR to R), two from (NR to E) and two from (R to E). We represented the original species status by county in grayscale and the updates in colors red, orange, and yellow (Fig. 2).

Our search for records from published manuscripts followed the basic structure and rules of a systematic review. The initial searches yield *n* = 32 manuscripts in Pubmed, *n* = 168 in Scopus, and *n* = 69 in Web of Science; for a total of 269 results. After screening and removing duplicate records, 220 manuscripts remained, and only 22 met our inclusion criteria, but only 17 of those were eligible and included specific Illinois county-tick data with especific tick numbers or information that allowed for the determination of a minimum number of ticks by species in that county. After examining the referenced materials of these 17 manuscripts, we identified 13 more manuscripts published before 31 December 2017, that met our inclusion criteria. However, we included all national tick distribution maps published before 1 August 2018, in determining the original status and distribution maps for *A. americanum, D. variabilis*, and *I.scapularis* leading to the addition of one more manuscript. The total number of manuscripts used as data sources was 31.

We contacted researchers from the 26 peer-review publications (excluding the five national tick distribution papers) whose manuscript(s) suggested that there was tick-level data for counties with baseline reports different than established, we excluded researchers with tick information from avian hosts. Three researchers provided the tick-level data used in their manuscripts and included data omitted from their published work; one researcher could not recover old data but gave us data from more recent, but unpublished efforts and two lead researchers are now deceased.

Prior knowledge of tick-level data (from personal communications with past and present collaborators) contributed to 2,406 records. These records were in tick collections that, at the time of this work, had not been reported to public collection databases. Few records were not cataloged, or their ticks identified, but, were identified and accessioned in response to our request. These data sources did not always report the number of ticks newly identified or accessioned in response to our request included within the data given to us.

Data sources contributing enough information to determine tick species, location of county, year of collection, and status (R, NR, or E) yielded 11 primary data sources, 15 secondary data sources, and 13 tertiary data sources (Tables 1–3). Primary sources accounted for 9,659 individual tick records in 100 counties: 4,045 *A. americanum* in 77 counties, 2,124 *D. variabilis* in 94 counties, and 3,490 *I. scapularis* in 46 counties (Table 4). Primary sources that received voluntary tick submissions provided information for the three tick species of interest and covered more counties than data sources using methods for tick collections that included dragging or fieldwork with vertebrates. Four of the primary data sources focused on a single county, two provided information on three and five counties, and five sources provided tick reports for 35 or more counties (Table 1).

Primary data sources reported all three life stages (adult, larva, and nymph) except for KCHD, who only reported adults and Kitron et al. 1991, who only reported larvae. We found the *A. americanum* by the end of 2017 established in 29 counties, 12 of those based on life stage information; *Ixodes scapularis* established in 40 counties, (six counties, based on life stage data). We found few *D. variabilis* larva or nymphs, so although this species is established in 33 counties, we only determined the established status, based on the life stage for two counties.

We attributed most of the updates to the distribution and status for all three species to previously untapped primary data sources. Of the 11 primary sources, those that housed tick collections or received voluntary tick submissions for passive surveillance efforts, identification, and or pathogen testing (N.E. Mateus-Pinilla, INHS [2018] entomological collection, USNTC [2019], IDPH, and TickReport [2019]) provided 4,700 tick records for ≥ 35 counties. Individual researchers sharing their data (M.E. Gilliam, J. Rydzewski, U. Kitron, and J. Nelson) accounted for 4,959 tick records covering one to five counties (Table 1).

Primary and secondary data sources provided the specific number of ticks and county location although, primary data sources offered more details for a tick record. In comparison, primary data for *A. americanum, D. variabilis,* and *I. scapularis* contributed to 90% (4,045/4,482), 80% (2,124/2,640), and 32% (3,490/10,898) of all tick records vs 10%, 20%, and 68% respectively from secondary data. Secondary sources accounted for 8,361 individual tick records across our three tick species of interest, 89% (*n* = 7,408) were *I. scapularis* (Table 4) and focused on one or two counties, except for Cortinas and Kitron (2006) and Nieto et al. (2018), who collected from 17 to 46 counties, respectively. Five secondary sources identified 437 *A. americanum* in 14 counties, five reported 516 *D. variabilis* in 35 counties, and 11 reported 7,408 *I. scapularis*

Table 4. Cumulative number of ticks (by species) and counties identified from primary, secondary and tertiary data sources

Data source	*Amblyomma americanum*		*Dermacentor variabilis*		*Ixodes scapularis*	
	Ticks	Counties	Ticks	Counties	Ticks	Counties
Primary	4,045	77	2,124	94	3,490	46
Secondary	437	14	516	35	7,408	35
Tertiary[a]	29+	11	76+	33	429+	65

[a]A '+' indicates it was only possible to extract a minimum number of ticks.

in 35 counties. Secondary sources offered more information about tick hosts compared to primary or tertiary data sources (Table 2).

Tertiary data sources provided an aggregate number of ticks, or an opportunity to estimate a minimum number of tick records from the text, tables, or figures, and provided categorical information designating a county as established or reported with collection-year or range of collection years. These tertiary sources contributed to the information in 11, 33, and 65 counties for *A. americanum*, *D. variabilis,* and *I. scapularis,* respectively (Table 4).

Of the 13 tertiary data sources, four were national distribution maps used to develop our original baseline status and county-level distribution maps. Three of the national distribution maps and two other tertiary sources, did not provide specific tick numbers. For eight of the tertiary data sources we were able to estimate a minimum number of ticks for a species in a county after reading the text and evaluating figures and tables. For one data source, we used the year of publication to indicate the relative year of tick collection based on the information in the text. Twelve tertiary data sources provided aggregate tick data between collection years and no specific year of the collection (Table 3). We present the estimated minimum number of ticks by species from tertiary sources (Tables 3 and 4).

Counties in need of surveillance by target tick species include those without tick reports 23, 4, and 25 for *A. americanum*, *D. variabilis,* and *I. scapularis*, respectively (Fig. 2). We found 62 counties with a tick report for each of the three tick species; However, 29 counties have an NR status for one of the three ticks species; 10 counties have an NR status for at least two tick species (Alexander, Christian, Clay, Douglas, Effingham, Ford, Massac, and White Counties have an NR status for *A. americanum* and *I. scapularis*; and Hamilton and Jefferson have an NR status for both *D. variabilis,* and *I. scapularis*). To date, Stark county is the only county without a single tick report for any of the three tick species (Supp Table S1 [online only], Supp Fig. S1 [online only]).

Discussion

This study used 18,020 tick records (Supp Table S1 [online only]), covering over 100 yr of data. We used a data inventory effort from data sources derived from the literature, entomological collections, and researchers willing and able to finalize old specimen identifications and to share their data with this project. By consolidating information from several data resources, we illustrated temporal changes in the first reports and spatial distribution maps of the three main vector ticks in Illinois, *A. americanum, D. variabilis*, and *I. scapularis*, as of December 2017. While the data used for this manuscript comes from the use of various strategies' in the collection of ticks across time and space, our work provides a critical update to the distribution, status, and knowledge of the first reports of these three tick species in Illinois.

Temporal changes in the timing of first reports observed from our results suggest under-reporting before 1985, an increase in tick occurrence and numbers over time, geographical expansion of these vectors, or new establishment for *A. americanum* and *I. scapularis* after 1985 (Fig. 1).

Even though we documented the wide distribution of these tick species in Illinois, we could assume that counties without a report for *A. americanum, D. variabilis*, or *I. scapularis* (23, 4, and 25, respectively) (Fig. 2) surrounded by counties with ticks (Supp Table S1 [online only], Supp Fig. S1 [online only]) are likely to have ticks. These gaps may relate to lack of surveillance and tick data from these counties, and there may be something unique about these counties influencing the occurrence of these ticks. Thus, the need for surveillance and research in these areas.

Dermacentor variabilis can be a vector for *Rickettsia rickettsii* (the agent of Rocky Mountain spotted fever) and *Francisella tularensis* (the agent of Tularemia) (CDC 2019c). Eight published manuscripts provided data on *D. variabilis* in Illinois (Tables 2 and 3). Cases of these illnesses are increasing in Illinois; however, the extent of human exposure to these ticks requires further assessment (Herrmann et al. 2014). The status updates from this manuscript facilitate directing future studies, disease, and tick surveillance efforts and assessments of risk of tick exposure.

Similarly to Wisconsin, Illinois saw a southwestern range expansion of *I. scapularis*, and an increase in density of *I. scapularis* on white-tailed deer during the late 1980s (Bouseman et al. 1990, French et al. 1992). *Ixodes scapularis* was first found in northwestern Illinois in the late 1980s. Therefore, it is assumed that the density of *I. scapularis* could be higher in the northern half of the state due to its proximity to areas where the tick was introduced (Cortinas et al. 2006). Our data support that the majority *I. scapularis* records came from the northern half of the state (Fig. 1); in agreement with a map from the CDC (2019b) supporting the wide distribution of *I. scapularis* in the northern regions of Illinois. Our observed increased number of records for *I. scapularis* during the last two decades may be due to increased passive surveillance in response to increases in public health concerns related to Lyme and other tick-borne diseases in Illinois and the United States.

We found *A. americanum* throughout the state of Illinois, although most of the reports were after 1985. The increased reports and updated distribution status of this tick species in Illinois have significant implications for public health. *Amblyomma americanum* is associated with the emerging vector-borne diseases STARI–Southern Tick Associated Rash Illness, Tularemia, and Ehrlichiosis which may have contributed to increased public interest, awareness and concerns leading to increased tick submissions during the last 20 yr (Mixson et al. 2006, Goddard et al. 2009, Tokarz et al. 2014). We present the reported cases of some of these human tick-borne diseases in Illinois in Fig. 3. We assume that the impact of these diseases on public health contributes to a surge in tick research that likewise influences tick submissions, identification efforts, and reporting. Besides, we assume that the aggressive, generalist feeding behavior observed at all life stages of *A. americanum* (Childs and Paddock 2003) and the growing range expansion of this tick in Illinois, will facilitate public awareness and submission of *A. americanum* specimens. Continuing to intensify the impact of this tick on human health in Illinois are the first reports of Heartland virus (IDPH 2018b) in 2018 in Illinois, and reports of Alpha-Gal Syndrome, an allergic reaction to the consumption of red meat following the tick bite from an *A. americanum* (Fischer and Hilger 2017).

Overall, we found 10 manuscripts that included *A. americanum* (Tables 1–3). The only distribution map for *A. americanum* in Illinois was by Springer et al. (2014). We base our distribution estimates on 4,045 records from primary data (90% of our 4,482 *A. americanum* records). We note the value of the primary data as these data sources allowed us to determine the establishment of a tick species in a county based on life stage, even when the numbers of ticks were less than six. We updated the status for *A. americanum* in 12 counties out of 29 counties newly defined as established, based only on life-stage information. The impact of primary data with clear and specific tick-level information including, the location of tick collection, life stage, and the number of ticks, is noteworthy.

Passive surveillance where tick specimens are voluntarily submitted to state or federal public health agencies is a tool to identify species presence (Childs and Paddock 2003, Springer et al. 2014, Barrett et al. 2015, Pak et al. 2019). However, it may not provide enough information to validate the origin of every tick collected. The effect is a tick report in a county when the tick came from a neighboring county or state for a tick collected from a highly mobile wildlife host such as a deer or bird.

The state or county of origin (where the host picked up the tick) may be different from the county of collection for ticks collected from a highly mobile wildlife host such as deer or birds. However, our tick occurrence record was the county of tick collection from the wildlife host. Similarly, a record of tick occurrence in a 'new' county from a human host without a travel history does not necessarily reflect on the life cycle and reproducing population of that tick in the county. While the lack of travel history of a human host or from a host associated with human movement (pet or livestock) is a limitation of this study, it points to the need of capturing this information to improve estimates of risk exposure and spatial certainty of the tick distribution, occurrence, and establishment by county.

Increased tick reports from passive surveillance may serve to recommend active surveillance (i.e., use of systematic field collection efforts to actively collect tick specimens using tick drags, flagging and removal of ticks from hosts in a county or location), to identify reproducing tick populations, and to determine the occurrence and status of a tick species in a county.

Overall, the literature search revealed a limited number of tick records that included both spatial and temporal information. Several reports in the literature did not provide exact numbers, but instead defined the status of *I. scapularis* and *A. americanum* as 'established', 'reported', or 'not reported' in a county (Dennis et al. 1998, Springer et al. 2014, James et al. 2015, Eisen et al. 2016), which was informative to meet the objectives of those manuscripts, but did not allow us to quantify their information and tally with the newly identified number of ticks from tick records in this work. This information may be more valuable when we try to determine density, abundance, and establishment of these ticks in a county.

We found that most secondary and tertiary sources (peer-reviewed literature) lacked specific tick-level information such as the number of ticks, life stage, and county of collection for a tick, collection-year, or day collected. Therefore, we note the value of reporting non-aggregated numbers of ticks, tick species, specific location, and exact date of collection within the publications. Many datasets lost in old technology storage units, disks, unreadable paper records are not retrievable, and we were not able to find the data from deceased colleagues, further supporting the value of publishing the dataset. This detailed and specific information can further our understanding of tick expansion, distribution, and risk of human exposure to tick bites.

Enlisting citizen scientists and supporting vector control staff in public health departments and even Illinois Mosquito Abatement Districts (some of which also collect tick data) can provide the means to collect entomological surveillance data. Their support can favor long-term research on the ecology, temporal distribution, and seasonal variation of tick populations that help researchers, scientists, and public health officials to identify areas of a substantial risk of exposure to tick bites. By supporting current and future tick identification, surveillance and tick research efforts, we can expand on the knowledge of spatial-temporal distribution and expansion of these vectors, inform risk assessments, direct and focus recommendations to citizens and their pets, and increase awareness among the medical community and the public at the regional and local level.

This study was not intended to evaluate variations in spatial and temporal trends in tick abundance, distribution or occurrence, or their relation to variation in tick-borne diseases in Illinois. However, we note the increase in tick-borne diseases from 1990 to 2017 that could explain an increase in the public interest, awareness, and first tick reports for *A. americanum,* and *I. scapularis* after 2000 (Fig. 1). Studying the relation between disease and tick trends on the geographical landscape could inform disease risk models and serve as a reminder of the medical importance of other tick species. Although *I. scapularis* is a tick species that warrants significant research and has been the most studied, other tick species cannot remain neglected.

We recognize the limitations of data collection in this study. We note the potential for duplicate records. One researcher may have published several manuscripts using the same dataset. Although we cross-referenced and evaluated publications by the same author if the tick information by year at the county level was the same across manuscripts for a researcher, we listed only one manuscript in the reference tables. Nonetheless, sometimes, it was unclear if tick records from manuscripts existed in public tick-data sources, entomological collections, or IDPH data, and consequently, we may have missed the identification of some duplicate records.

The sources of data differed, but so did the year and collection methods. New establishment of tick species can only be accurately assessed if data collection methods are comparable across time and geographical landscape. The heterogeneity of data and lack of harmonization of data collection across time and space makes it very difficult to evaluate the exact temporal changes and spatial trends in tick reports and establishments, or to make precise estimates about timelines for expansion and establishment of these species. To evaluate these changes, we would require the same or very similar field data collection methods implemented at the same location at different times. Thus, we emphasize the need for a national tick database with raw and specific tick-level data that allows for the comprehensive undertaking of the evaluation of temporal tick expansion over time and space.

This work was not intended to be a systematic review nor a survey design effort. Although we used tools to select, assess, include or exclude published manuscripts following the basic structure of a systematic review; and, although we reached out to past and present collaborators, we did not follow a survey design to capture all possible available data. As such, our results only reflect occurrence and status change based on our best available knowledge. We assume that we missed data sources. Therefore we cannot make final and definitive conclusions about temporal changes in tick expansion.

We identified over 18,000 individual tick records; this is likely an underestimate because not all studies incorporated into our dataset provided specific tick numbers. For example, if an author recorded 102 deer infested with a species of the tick but did not provide the number of ticks per deer, we estimated a minimum number of 100 ticks, represented as 100+ (Table 3). However, we did not include those estimates in the calculations of tick numbers to update the status in Fig. 2 or the text because the numbers may have been off by unknown orders of magnitude.

We chose the conservative approach of using precise tick numbers to inform our estimates of status updates by county. In Table 4, we illustrate the contributions of primary and secondary data sources, and the lost opportunity to gain specific tick numbers from tertiary data sources.

We integrated historical tick information for Illinois by including data from publications without the tick-level data (i.e., we lacked raw data). Often, ticks were collected by different groups, data were aggregated for the range of years of collection, reported without life stage, or there was a delay in tick identification or data sharing with IDPH at the time of this work. Our status and distribution maps and tick numbers (Supp Table S1 [online only]) highlight the lack of tick data for some counties in Illinois and serve us to focus on future surveillance efforts.

Conclusion

This manuscript updates the first reports, occurrence, distribution, and status of the three main vector tick species in Illinois: *A. americanum, D. variabilis*, and *I. scapularis* in 77%, 96%, and, 75% of the 102 counties. *Ixodes scapularis* has been the primary focus of tick studies in Illinois (Tables 2 and 3). The relation between *I. scapularis* density, and the risk of human exposure to a tick bite is unclear. However, we suggest that additional surveillance is warranted in the central and southern parts of Illinois (Fig. 2) (CDC 2019a), where the tick is either not reported, or reported but with a remaining potential for becoming established.

We were unable to estimate precise timelines for expansion and the establishment of these ticks in light of the heterogeneity of the data. However, we document temporal and increasing trends in the number of counties with tick first report, and with a status updated over recent decades. Our depiction of the data helps to visualize temporal differences in tick occurrence (Fig. 1) and to identify areas in need of additional surveillance (Fig. 2).

We often attributed the determination of the distribution and status of the three tick species to unexplored primary tick-level data. Primary data provided the most comprehensive tick-level information followed by secondary and tertiary data. Primary data allowed for the determination of status by the number of ticks and life stage, it provided the highest number of tick records, and it was easier to extract their information compared to the other data sources. Voluntary submissions from passive surveillance efforts and tick collections provided higher numbers of ticks from more counties compared to secondary and tertiary data sources (Table 4).

Our updated information indicates that all three tick species are widespread in Illinois and established in many counties. Our work may serve to recommend active surveillance to identify reproducing tick populations at predetermined locations and to determine the occurrence and status of a tick species in a county. We highlight the need for tick surveillance efforts in areas without tick records or with a reported status.

Some of the detailed tick information from secondary or tertiary was lost in aggregated or summary data. However, there may be lost records in unaccounted entomological collections with identified and unidentified tick specimens. Some of the specimens and data responsible for our updates existed for several years but remained unknown. It is unclear how many specimen collections we missed, yet their contribution to the understanding of the geographic and temporal expansion of these ticks may be significant. We found records that were lost because the tick collections were unknown, the specimens from entomological collections were not identified, archived, or digitized until recent years; or, the tick-level data were not published with the manuscripts.

Although not every tick carries a pathogen, our updated maps can inform the medical community about the occurrence of these disease vectors in the area. Increase awareness of tick occurrence may lead to the consideration of differential diagnosis that improves recognition and reporting of tick-borne diseases.

We note that changes in the visual trends of diseases transmitted by ticks suggest the importance for understudying the occurrence, status, and distribution of ticks of medical significance of humans and domestic animals. Both passive and active surveillance play a role in this effort. For example, the incidence of the emerging pathogen *Ehrlichia chaffeensis* is 10-fold higher based on active versus passive surveillance (Paddock and Childs 2003). However, passive surveillance can reveal if a tick species is present in an area. For example, *Amblyomma maculatum* (Koch) was detected in 2008–2009 in Johnson and Union Counties in southern Illinois (NE Mateus-Pinilla passive surveillance based on voluntary submissions). *Amblyomma maculatum* is a known vector of *Rickettsia parkeri* (Paddock et al. 2010), an emerging spotted fever pathogen. Our findings support the need for additional efforts to determine the distribution and occurrence of this tick in Illinois. After all, it is essential to determine the spatial, temporal, and habitat information related to the distribution of ticks (Nieto et al. 2018) and the tick-borne diseases that they transmit.

Cases of tick-borne diseases are increasing in Illinois. However, the extent of human exposure to these ticks requires further assessment (Herrmann et al. 2014). The status updates from this manuscript facilitate directing future studies, disease and tick surveillance efforts and assessments of risk of exposure in areas with and without the vector. Besides, it will contribute to the development of risk models for tick-pathogen transmission in Illinois.

There is a need for a systematic, national vector surveillance program that supports publishing tick-level data including collection method, tick species, number of ticks, life stage, specific date, and location of the collection. The program can encourage and support sharing data with public health agencies and conducting risk analyses of human exposure to tick bites and tick-borne diseases. A national vector surveillance program can intensify surveillance efforts, improve synergies between researchers and agencies conducting target outreach to the public, and supporting the detection of tick collections that may remain to be identified, digitized, and shared. The program can emphasize the importance of sharing raw data, using multiple surveillance methods, and submitting voucher specimens to entomological collections that keep accurate and organized data records shared with state public health units. We recognize the value of creating guidelines to facilitate the sharing of data by the scientific community where scientists receive some credit in support of the scientific and academic expectations of their institutions.

The data recovery effort is a powerful tool to evaluate the historical status and changes in distribution, expansion, and invasion of ticks, and it sets an opportunity to guide future studies. We assert the value in searching for unused or underused data sources, funding strategies to identify, archive, maintain, report tick data to state health agencies like IDPH, as well as to sites broadly accessible to researchers (e.g., the CDC's tick module in National Arboviral Surveillance System ArboNET https://wwwn.cdc.gov/arbonet/). We emphasize the importance of conducting active surveillance in counties with tick reports and counties contiguous to areas with tick reports and with established tick populations.

Supplementary Material

Supplementary data are available at *Journal of Medical Entomology* online.

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