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A systematic review of the associations between mosquito- and tick-borne diseases and vector research in the United States

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Tick- and mosquito-borne diseases in the United States are occurring at increasing rates and are heterogeneously distributed among the states. The allocation of public health resources and the attention of a research community on ticks and mosquitoes should be proportional to the number of reported human disease cases in each state. We conducted a systematic literature review of all publications on field-based studies of mosquitoes and ticks as a proxy for resource availability and research attention and compared these to the number of human tick- and mosquito-borne disease cases. The results showed that although some states have proportional publications and human disease, many deviate. This study highlights many states that have low numbers of publications on ticks or mosquitoes yet high incidence of human disease and other states that have high number of publications on ticks or mosquitoes yet a low disease incidence. This study may help public health agencies and the research community prioritize the need for increased research attention in states with the greatest disease burden.

Keywords: resource allocation, vector-borne disease, research attention

Introduction

Human morbidity and mortality from vector-borne diseases are increasing in the United States (Rosenberg et al. 2018). Most of these vector-borne disease systems exist in sylvatic enzootic cycles involving non-human amplification or reservoir hosts with bridge transmission (ie spillover) to humans. The natural nidality of these different pathosystems is diverse, resulting in spatially and temporally heterogeneous distributions of human disease; human Lyme disease is concentrated in the Northeast and upper-Midwest (Schwartz et al. 2017), whereas West Nile virus disease is concentrated in urban areas, with the largest number of human cases found in California and Texas (McDonald et al. 2021). Although over 20 different vector-borne diseases have been documented to circulate in the United States, tick-borne diseases account for 77% of all reports and have more than doubled in number from 2004 to 2016 (Rosenberg et al. 2018). Among all the tick-borne disease, Lyme disease was the most common reported and ranked sixth among all notifiable infectious diseases in the United States in 2017 (Beard et al. 2021). The reported case numbers of Lyme disease have increased from 36,429 in 2016 to 89,468 in 2023 (Centers for Disease Control and Prevention 2025).

Members of the US Congress advocate that there should be a correlation between the allocation of funding from the National Institutes of Health (NIH) by disease and the distribution of disease burdens and costs in the population (Institute of Medicine Committee on the NIHRP-SP 1998). Accordingly, a positive association exists between NIH funding and the burden of 46 different chronic and infectious diseases (Ballreich et al. 2021). Similarly, the allocation of public health resources and the attention of the research community on different vector-borne diseases should be proportional to the disease risk and severity in a region. The objective of our study was to compare tick- and mosquito-borne disease incidence with the amount of research on ticks and mosquitoes in each state. To achieve this, we assembled all notifiable human tick- and mosquito-borne disease data between 2011 and 2019 available from Centers for Disease Control and Prevention (CDC). We then used peer-reviewed publications reporting field-based tick and mosquito research from 2015 to 2019 in each state as a proxy for research attention to the different vector-borne disease systems in the United States. This timeline ending before the COVID-19 pandemic that started in 2020 avoided conflict due to inconsistent reporting of vector-borne diseases, reduced

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field-based research activities during isolation, and changes in the rate of publications (Weldon et al. 2022). We used these data to test the hypothesis that that a positive relationship exists between publications and human disease in each state.

Methods

Aggregation of Tick- and Mosquito-Borne Human Disease Data

We gathered the data on the number of human tick-borne and mosquito-borne disease cases from 2011 to 2019 from the Centers for Disease Control and Prevention (Supplementary Table S1). Case data was reported based on patient state of residence and includes both confirmed and probable cases, as described below. The date did not extend prior to 2011 for data consistency because some diseases were not nationally notifiable prior to 2011. Tick-borne diseases included Lyme disease, Powassan virus disease (neuroinvasive and non-neuroinvasive), spotted fever rickettsiosis, tularemia, babesiosis, anaplasmosis (*Anaplasma phagocytophilum*), ehrlichiosis (*Ehrlichia chaffeensis*), ehrlichiosis (*Ehrlichia ewingii*), and undetermined ehrlichiosis/anaplasmosis. Mosquito-borne diseases included West Nile virus disease (neuroinvasive and non-neuroinvasive), La Crosse virus disease (neuroinvasive and non-neuroinvasive), Jamestown Canyon virus disease (neuroinvasive and non-neuroinvasive), eastern equine encephalitis virus disease (neuroinvasive), St Louis encephalitis virus disease (neuroinvasive and non-neuroinvasive), dengue fever and dengue hemorrhagic disease (local), chikungunya virus disease (local), and Zika virus disease (local). We only included locally acquired cases for the three *Aedes*-borne diseases (dengue, chikungunya, and Zika), which only occurred in Texas and Florida (Supplementary Table S1).

Publication Search

We conducted a systematic literature review using Web of Science between 2015 and 2019. The search terms used were "Tick" or "Mosquito," and "State" for topic search, and publication year. District of Columbia was not included in the search. We did not include the year 2020 and beyond because of the impact of COVID-19 on field-based studies. The search for tick publications from 2015 to 2019 was conducted in October–November 2022 and June–November 2024, whereas the mosquito publication search was done in October–November 2022 and June–July 2023. Inclusion criteria included primary literature on (1) field studies involving ticks or mosquitoes in a given state and (2) focus on ticks and mosquito species that were vectors of infectious agents of diseases for humans. Exclusion criteria included (1) review papers, (2) studies of ticks or mosquitoes only performed in a laboratory with no involvement of field activities (eg laboratory studies without collecting samples from the field), (3) studies only on nuisance ticks or mosquitoes (tick or mosquito species not known to transmit human disease-causing pathogens but cause direct harm or annoyance), and (4) studies using passive collection for ticks or mosquitoes. The intention of these inclusion and exclusion criteria was to capture studies conducting field-based research on ticks, mosquitoes, and associated diseases in each state. Passive collections of these vectors using community science can be orchestrated from anywhere and can be conducted nation-wide which deviates from the hypothesis being tested. Each publication was reviewed by at least two authors and any paper with uncertainty was discussed with Gabriel L. Hamer. Studies with field activities in multiple states counted toward each state. Each publication that met inclusion criteria counted for the respective state in the search, and tick and mosquito studies were recorded separately.

Graphical Analysis and Mapping of Data

Spearman correlation was used to analyze the trend of the total tick- and mosquito-borne disease cases and publications over the 10 years. The publication number and number of disease cases were corrected by million population in the figures of the main text while the Supplementary Material shows the same figures with publications and disease cases uncorrected by background population. The 2020 U.S. census data were used as the total population of each state (U.S. Census Bureau and U.S. Department of Housing and Urban Development 2020) (Supplementary Tables S2 and S3). The publications per million population and disease incidence (disease case numbers per million population) were mapped for each state. They were also analyzed using a linear regression model to explore the relationship between population and disease with disease number per million population as the independent variable and publication number per million population as the response variable. The heteroskedasticity of the regression model was checked using the White test and failed to reject the null hypothesis (there is no heteroskedasticity in the regression model) (P-value = 0.74 and 0.25 for tick and mosquito analyses, respectively). Residuals from the linear regression model were obtained by subtracting the expected corrected publication number of the state from the actual corrected publication number of the state. We interpret the positive or negative residuals to represent a deviation from the mean of a linear and positive relationship between the publications per million population and disease per million population for each state. All mapping and analysis were conducted using R (R version 4.4.1, The R Foundation for Statistical Computing, Vienna).

Results

Tick- and Mosquito-Borne Diseases During 2011–2019

A total of 427,863 tick-borne disease cases were reported to CDC during the nine years from 2011 to 2019 (Supplementary Fig. S1), with 75% being Lyme disease (318,986), followed by spotted fever rickettsiosis (39,850) and anaplasmosis (33,715) (Supplementary Table S2). Lyme disease cases were mainly reported from states in the Northeast, including Pennsylvania (75,237, 23.6%), New Jersey (39,742, 12.5%), and New York (34,135, 10.7%). Correcting Lyme disease cases by state population (per million population) resulted in the highest incidence in Vermont (10,636/million), Maine (9,543/million), and New Hampshire (8,057/million).

Over the 9-year period from 2011 to 2019, a total of 22,710 mosquito-borne disease cases were reported from 50 states (Supplementary Fig. S2). West Nile virus disease (neuroinvasive and non-neuroinvasive) was the dominant mosquito-borne disease, with 21,057 (92.7%) cases, followed by La Crosse virus disease with 667 (2.9%), and locally acquired dengue virus infection with 345 (1.5%). The highest number of West

Nile virus disease cases (neuroinvasive and non-neuroinvasive) were documented in California (4,037, 19.2%) followed by Texas (3,415, 16.2%) and Colorado (1,114, 5.3%) (Supplementary Table S3). Correcting West Nile virus disease cases by state population resulted in the highest incidence in South Dakota (956/million), North Dakota (792/million), and Nebraska (561/million).

There was a significant positive Spearman correlation between the number of tick-borne disease cases and time (P-value = 0.01, r_S = 0.82), whereas the number of mosquito-borne disease cases did not have a strong correlation with years (P-value = 0.84, r_S = −0.08). The number of mosquito-borne disease case number in the United States has been relatively stable except for a dramatic increase in 2012 due to the West Nile virus (WNV) outbreak with an epicenter in Texas where a total of 1,868 cases were reported. The relatively low numbers reported in 2011 and 2019 resulted from a reduction of WNV cases in those years compared to other years.

After correcting the disease cases by million population in each state in 2020, the number of tick-borne diseases followed a similar distribution, with most cases concentrated in the Northeastern states but slightly extending to the Southeast (Fig. 1a). However, the rank of mosquito-borne disease number from each state changed with the highest corrected number of mosquito-borne disease cases being South Dakota, followed by North Dakota, Nebraska, and Colorado (Fig. 2a).

Publication Search During 2015–2019

A total of 995 and 1,063 publications on ticks and mosquitoes were found on Web of Science from 2015 to 2019 using the search terms “Tick” + “State” and “Mosquito” + “State,” respectively. Based on the inclusion and exclusion criteria, 264 and 215 publications were included for tick and mosquito, respectively (Supplementary Table S4 and Figs 3 and 4). During 2015–2019, no significant correlation was detected between year and publication for both tick and mosquito research (P-value = 0.51 and P-value = 0.84, r_S = 0.40, and r_S = −0.08, respectively). Among the 50 states, California had the most tick publications (34, 12.8%) over the five years, followed by New York (21, 8.0%), Virginia (17, 6.4%), and Connecticut (14, 5.3%). Out of the 215 mosquito publications, Florida had 61 (28.4%) publications over the 5 years, followed by Texas (13, 6.0%) and California (12, 5.6%). There were 12 and 13 states with zero publications on ticks and mosquitoes, respectively, over the five years. After the correction by state population, Connecticut had the highest number for tick publications, followed by Montana, Vermont, and Oklahoma (Fig. 1b), whereas Hawaii was the top state for mosquito publications, followed by Florida, Alaska, and North Dakota (Fig. 2b).

Relationship Between Diseases and Publications

The linear regression analyses between the numbers of publications and disease cases per million population revealed different patterns for ticks and mosquitoes (Fig. 3). A positive relationship was only significant between the corrected number of tick-borne disease cases and tick publications (P-value < 0.001, R^2 = 0.25), although with a weak fit, whereas the number of mosquito-borne disease cases and mosquito publications per million were not significantly related (P-value = 0.45, R^2 = 0.01). With tick data, the residuals from the linear regression model ranged from −1.61 to 2.96 (Fig. 4a and c). Among the 50 states, 17 states had positive residuals, whereas 33 states had negative residuals. Delaware had the lowest residual (−1.61), followed by Pennsylvania (−1.01), Indiana (−0.87), and New Jersey (−0.81), whereas Montana (2.96), Oklahoma (2.21), Connecticut (2.13), and Mississippi (1.95) had the highest residuals. For mosquito data (Fig. 4b and d), the residuals from the linear regression ranged from −1.18 to 2.65, where 28 states had positive residuals and 22 states had negative residuals. South Dakota had the lowest residual (−1.18), followed by Nebraska (−0.98), Wyoming (−0.78), and Arizona (−0.77). In contrast, Hawaii had the highest residual (2.65), followed by Florida (2.12), Alaska (2.02), and North Dakota (1.48).

When considering the relationship between uncorrected numbers of publications and disease cases on both ticks and mosquitoes, we still see positive trends (Supplementary Fig. S5). States with positive or negative residuals when using the corrected data generally remained consistent with the uncorrected data (Supplementary Fig. S6). Among the biggest difference for the uncorrected tick data is that California has the highest residual, meaning they have a much larger number of tick publications relative to tick-borne disease cases. Another large difference is that Florida had the largest residual for the uncorrected mosquito data, meaning they had a much larger number of mosquito publications relative to mosquito-borne disease cases.

Discussion

Our study revealed a broad positive relationship between the number of tick-borne disease cases in each state of the United States and the number of publications in those states reporting results from field-based research. This implies that the burden of human disease drives attention by researchers from academia, public health, and other entities. This relationship between disease and publications was stronger for ticks than it was for mosquitoes. This positive relationship was observed in NIH funding allocation, where specific diseases had associations between the amount of funding and the number of deaths and hospitalizations (Sampat et al. 2013). Among the diseases evaluated, AIDS, diabetes mellitus, and perinatal conditions received more funding than expected, while depression, injuries, and chronic obstructive pulmonary disease were underfunded based on disease burden (Gillum et al. 2011). These other findings were similar to how increases in human vector-borne diseases in the United States have increased the amount of available NIH funding for those disease systems (Kading et al. 2020). Therefore, more funding in states affected by vector-borne diseases fuels more research which helps to explain this study’s observation of a positive relationship between tick-borne diseases and publications.

One of the most informative aspects of these results is the identity of states that deviate from this relationship of human tick- and mosquito-borne disease cases and peer-reviewed publications. For example, states including Montana, Oklahoma, and Connecticut had a large number of publications on tick-based research in those states, although they had a relatively lower incidence of human tick-borne disease cases. Of the 14 publications in Connecticut reporting field-based research on ticks in that state, 6 (43%) included authors from the Connecticut Agricultural Experiment Station, the first agricultural experiment station in the United States resulting in a long

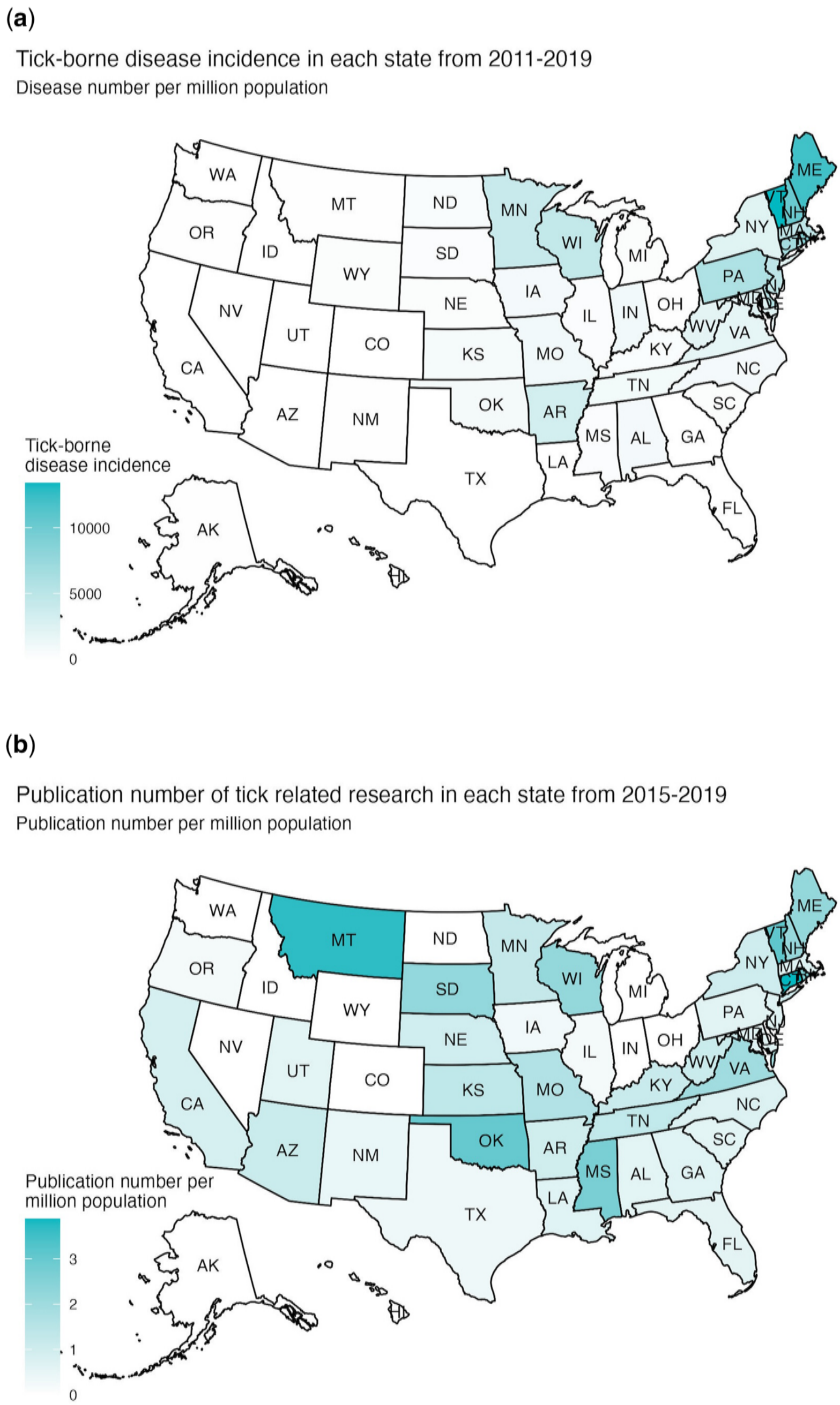

Fig. 1. Map showing the number of tick-borne disease cases and related research publications per million population in each state from 2011 to 2019. Panel a: Tick-borne disease incidence (cases per million population) in each state from 2011 to 2019. Panel b: Publication numbers per million population of tick-related research in each state from 2015 to 2019.

history of robust research (Maynard 1994). Although Montana had 4 tick publications, when corrected for the population of the state, this was a relatively large number given the low incidence of reported tick-borne disease cases. Montana has documented 91 cases of Lyme disease, 50 cases of spotted fever rickettsiosis, and 34 cases of tularemia, but once corrected for background population size, the state ranks 35 in terms of the incidence of tick-borne disease cases. As *Ixodes* sp. vectors are not established in Montana, the 91 Lyme disease cases are likely travel-associated. On the other extreme, Pennsylvania, Delaware, and New Jersey were states with a high burden of tick-borne disease cases but few tick publications. These states

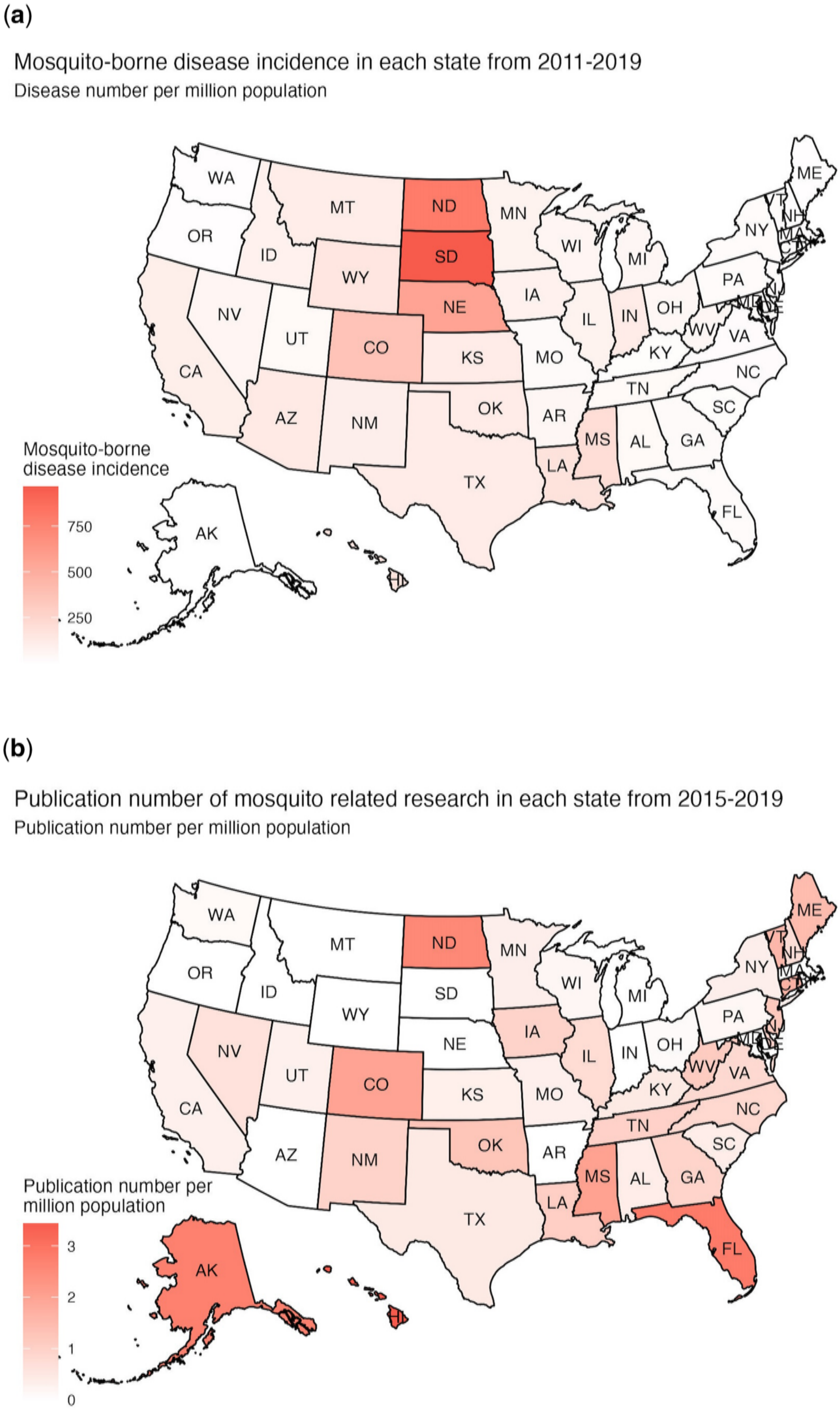

Fig. 2. Map showing the number of mosquito-borne disease cases (panel a) and related research publications (panel b) per million population in each state from 2011 to 2019.

ranked 6th, 7th, and 8th, respectively, in the corrected incidence of tick-borne disease cases, which were primarily driven by large populations of *Ixodes scapularis* Say, resulting in autochthonous cases of Lyme disease (Pepin et al. 2012). Pennsylvania, Delaware, and New Jersey had 8, 0, and 21 publications from field-based tick research and once corrected for population size, these states ranked 29, 39, and 27, respectively, in terms of publications reporting field-based research. For the uncorrected data comparison, California had a large number of publications on ticks relative to tick-borne disease. California has a large number of universities and public health agencies conducting research on ticks resulting in publications. While California ranked 31st in the number of tick-borne disease cases and despite having *I. pacificus* and *B.*

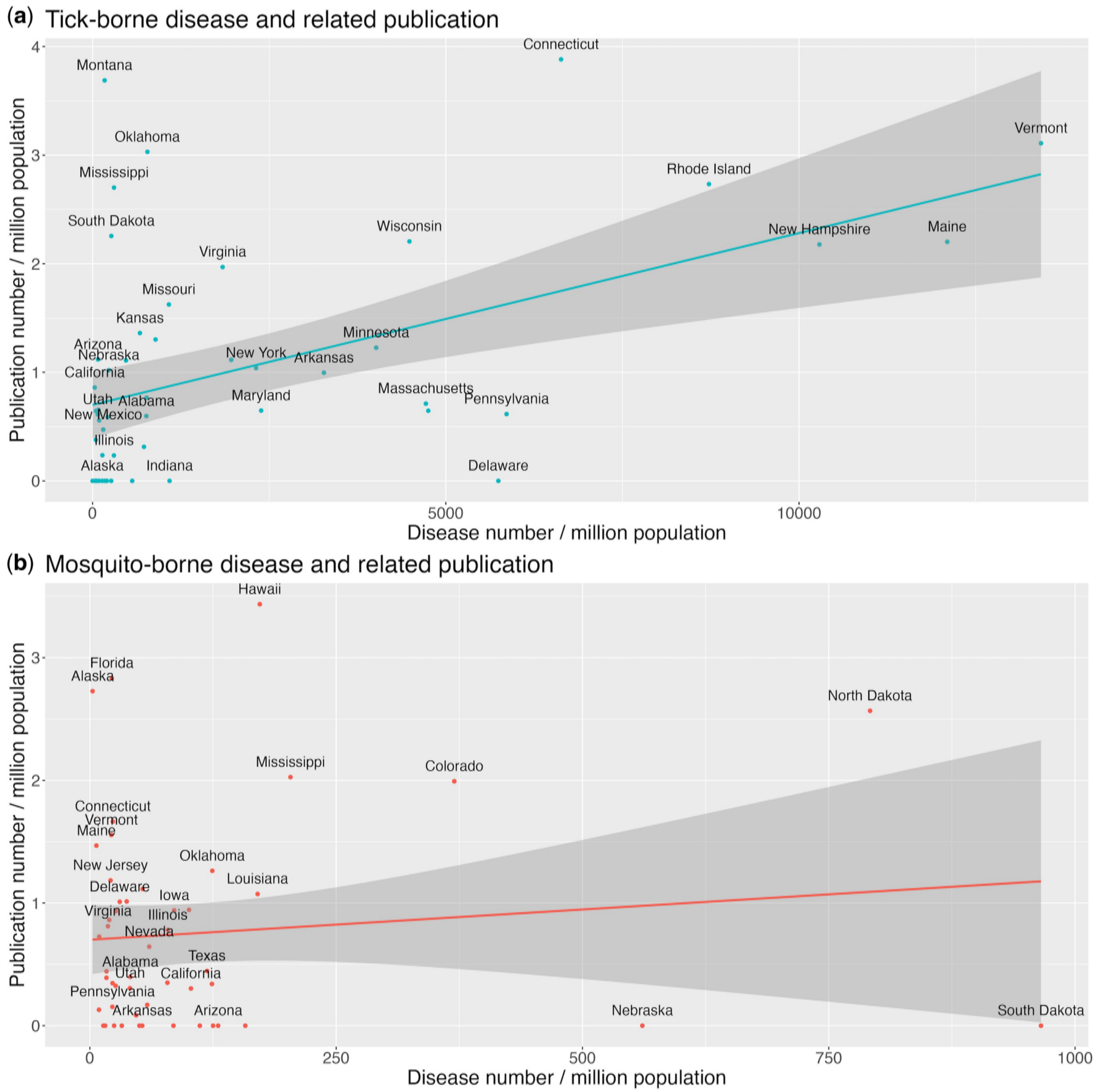

Fig. 3. Linear regression of corrected publication (2015–2019) and disease case (2011–2019) numbers of 50 states. The grey area indicates the 95% confidence interval. Panel a: Regression of tick-borne disease incidence (cases per million population) and publication number per million population of each state. Panel b: Regression of mosquito-borne disease incidence (cases per million population) and publication number per million population of each state.

burgdorferi, the density of infected nymphs tends to be lower than that of *I. scapularis* in the northeast (Lehane et al. 2021).

The deviation from the relationship for mosquitoes was lower than it was for ticks. For example, the regression between mosquito publications and mosquito-borne disease had several states with positive residuals, indicating a larger number of publications and a lower burden of disease. Florida was one of these states and indeed, Florida has not experienced the intense WNV amplification in enzootic cycles and spill-over to humans similar to other states; Florida ranked 26 of all states based on raw WNV case numbers and ranked 45 of all states based on cases corrected for population size. Mechanisms for this low spill-over to humans in Florida could be due to several factors, including an avian community less conducive to WNV amplification (Levine et al. 2016) as well as effective mosquito control. On the other extreme, several states have negative residuals indicating a relatively large disease burden due to mosquito-borne diseases but very few mosquito publications. These states included South Dakota and Nebraska, which were in the Central Great Plains where intense amplification of WNV, principally driven by *Culex tarsalis* Coquillett in more rural regions (Rhodes et al. 2023), has yielded a high incidence of human disease given the low population density (Lindsey et al. 2010). These results show that the number of publications resulting from field-based research in these states has been relatively low during the 5-year search period (2015–2019)

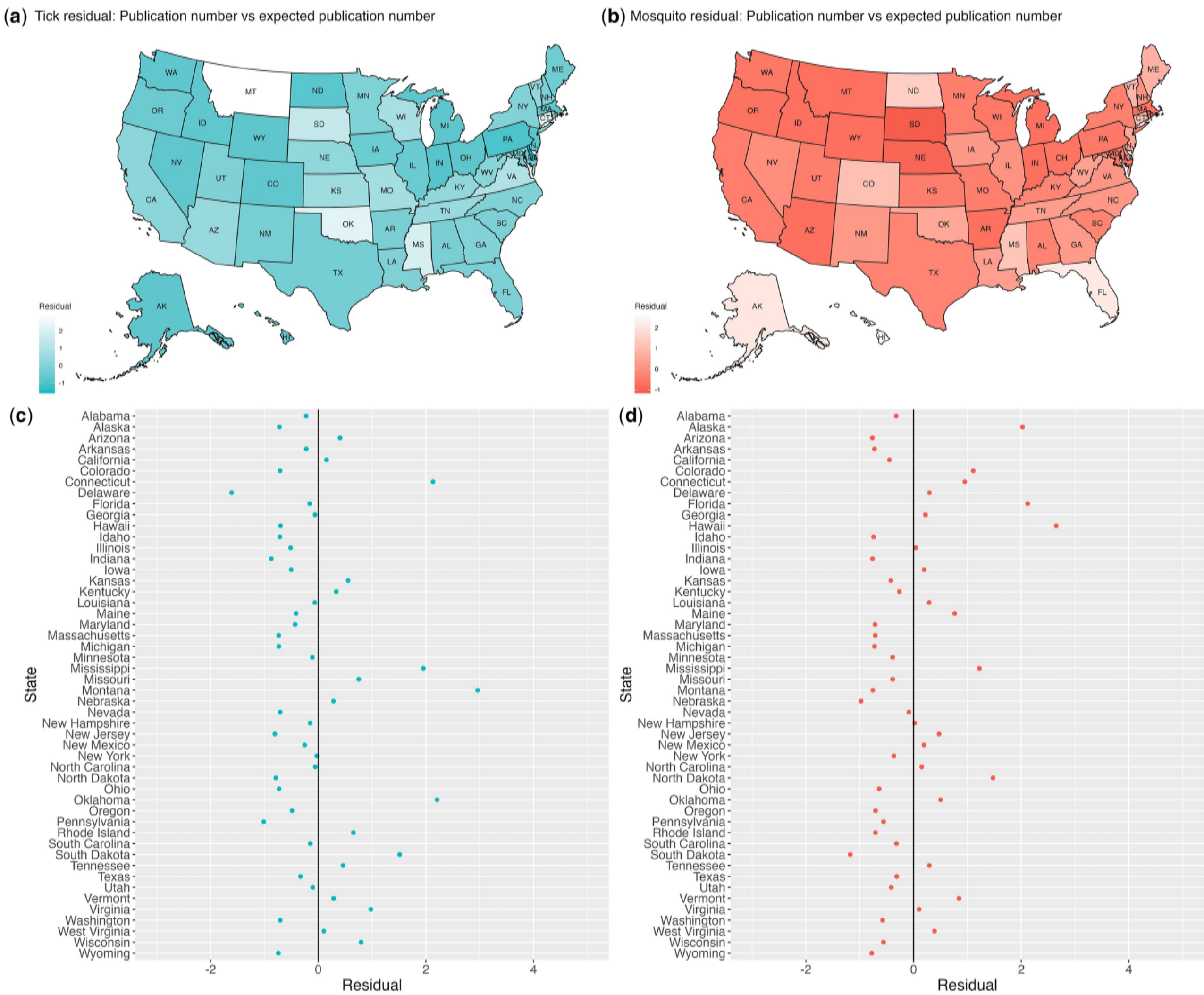

Fig. 4. Residuals of the corrected publication number from the linear model fitting corrected publication and disease case number for each state by tick- (Panels a, c) and mosquito-borne diseases (Panels b, d). States with larger negative residuals are the states with larger disease cases per million population and lower number of publications per million population.

compared to this high burden of human disease. While interpreting the number of publications relative to disease cases, we only are judging a pre-COVID-19 time period, which would be influenced by significant events occurring in this period, such as the emergence of Zika virus in the Americas. If this same systematic review was conducted in prior or future decades, the results of specific states would likely be different.

Funding for research in any given state that results in field-based research and peer-reviewed publications comes from several sources including governmental agencies at the federal (NIH, CDC, US Department of Agriculture, Department of Defense, etc.), state, and county levels. Additionally, funding can come from NGOs (eg American Mosquito Control Association, Bay Area Lyme Foundation, etc.). Finally, the CDC allocates funds to states through the Epidemiology and Laboratory Capacity Program (ELC) and even though these funds might not directly fund field research projects, they increase diagnostic capacity and facilitate research that generates peer-reviewed publications. For example, 12 studies within the papers meeting inclusion criteria for this study acknowledged the CDC ELC funds in their study that conducted field-based research on ticks or mosquitoes (Anderson et al. 2015, Harris et al. 2015, Varnado and Goddard 2015, Shepard et al. 2016, Varnado and Goddard 2016, Billeter et al. 2017, Goddard et al. 2017, Bradt et al. 2018, Cartner et al. 2018, Kovach and Smith 2018, Dunphy et al. 2019, Richards et al. 2019). Pennsylvania State University and Cornell University were the recipients of a CDC Training and Evaluation Center award (Centers for Disease Control and Prevention 2024a), which does not directly funding research, but through the training of students and evaluating tick control approaches, will undoubtedly led to peer-reviewed publications involving field-based research in the Northeast (Lehane et al. 2024). This will help address the deficiency of tick publications relative to the high burden of human tick-borne disease in the region.

Another mechanism likely underlying the heterogeneity in the number of publications in each state observed by this study is the variation in tax-payer dollars that enter local vector control operations. This variation in funding results in heterogeneity in the size of the vector control community among different states that our past study identified (Hamer 2016). Many county's public health departments or other divisions allocate tax dollars for the dedicated purpose of funding vector surveillance and control. Insufficient funds from these local tax dollars results in limited infrastructure that is needed to facilitate research activities, whether they are done internally to the local agency or in collaboration with academic or other partners. On the other end of this spectrum, some states and counties have well-funded county vector control programs, which often involve robust research done internally or with partners. For example, the large and sustained vector surveillance program at Harris County Mosquito and Vector Control Division in Texas has facilitated a large number of publications on mosquitoes performed internally to their agency (Vigilant et al. 2020) as well as through partnerships with academia (Dennett et al. 2007). California and Florida, states with a large vector control community (Wekesa 2015, Kondapaneni et al. 2021) due to large budgets from local taxpayers (Peper et al. 2022), have a large number of publications reporting field-based research on ticks and mosquitoes, including many that met the inclusion criteria in this study.

Variation in local tax-payer dollars that facilitate research at the local level likely impacts the results of this study on mosquitoes more than it does on ticks. This is because mosquito control has historically been the focus of the area-wide programs conducted by local agencies whereas the protection of the public health from tick-borne diseases falls on the responsibility of the public (Burtis et al. 2024). Funding for mosquito control is often driven by nuisance mosquitoes which is often the primary concern from the public, even when the risk of mosquito-borne pathogen exposure is present (Dickinson and Paskewitz 2012). This context likely results in a weaker relationship between publications and disease for mosquitoes compared to ticks. For example, Florida has many large and well-funded mosquito control programs such as Lee County Mosquito Control District, which received USD $25.7 million in FY 2021–2022 (The Balmoral Group 2023), and this large funding from local taxation has been driven by the large number of nuisance salt marsh mosquitoes. Although our current study would have excluded publications focused only on nuisance mosquitoes, these funds and capacity generated by this nuisance concern benefit research focused on mosquito vectors of human disease-causing pathogens and thus contribute to the large number of publications included for Florida in this study. This anomaly of Florida having many more mosquito publications compared to mosquito-borne disease cases is emphasized even more by the uncorrected comparison of data (Supplementary Fig. S6).

The disease data included in this study came from 2011 to 2019 and the publication range from 2016 to 2019. We did not include the identical disease and publication range as part of the objective was to determine how the observation of human disease cases leads to changes in policy, funding decisions, and research activity. For example, Bourbon and Heartland viruses were recently discovered tick viruses with original human cases observed in 2014 (Roe et al. 2023) and 2009 (Centers for Disease Control and Prevention 2024b), respectively. Following these human cases, the CDC and other researchers initiated targeted surveillance of local tick populations that were found to be infected with Heartland virus. This work on Heartland virus was conducted in 2012 and published in 2013 (Savage et al. 2013). This timeline captures the 3- to 4-year lag between the observation of human disease cases, related research activities, and when the research is published. The disease data included for this national-level analysis were restricted to those that were notifiable. Additional vector-borne human diseases that were not notifiable included Colorado tick fever, Heartland virus disease, and Bourbon virus disease, although the numbers of these cases would be very small compared to the notifiable tick-borne diseases. Finally, the human disease case data used in this study was based on location of case residence and not the location of exposure, which introduces limitations into the analysis.

We did not attempt to categorize publications on mosquitoes or ticks into different categories such as basic and applied. Although following the introduction of a new vector-borne disease threat, publication focus would likely shift from basic research to applied research over time as the system first needs to be understood before the field can focus on protecting humans from exposure. However, the vector-borne disease landscape is also constantly changing with new pathogens, increases in human disease, changing distributions of vectors, and other factors so the need for more basic research persists.

In summary, we found that the number of field-based publications generally had a positive relationship with tick- and mosquito-borne disease burden, although deviations were observed in certain states. We hope that this study helps to prioritize the need for increased research attention in states with a high burden of tick and mosquito-borne disease, but relatively low research activity based on the data obtained from this systematic literature review.

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Author contributions

Yuexun Tian (Data curation [equal], Formal Analysis [equal], Methodology [equal], Supervision [supporting], Visualization [equal], Writing—original draft [equal], Writing—review & editing [equal]), Lauren DeWitt (Data curation [equal], Formal Analysis [supporting], Writing—original draft [supporting], Writing—review & editing [equal]), Ryan S. Almeida (Data curation [equal], Formal Analysis [equal], Methodology [equal], Visualization [supporting], Writing—original draft [supporting], Writing—review & editing), Melinda Clark (Data curation [equal], Writing—review & editing [equal]), Daniel Obregon (Data curation [equal], Writing—review & editing [equal]), Sophie Adame (Data curation [equal], Writing—review & editing [equal]), Taylor Davis (Data curation [equal], Writing—review & editing [equal]), Nicole E. Mendez-Maio (Data curation [equal], Writing—review & editing [equal]), and Gabriel L. Hamer (Conceptualization [equal], Data curation [equal], Formal Analysis [equal], Methodology [equal], Supervision [equal], Writing—original draft [equal], Writing—review & editing [equal])

Supplementary material

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Conflicts of interest

None declared.

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