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1849 C STREET NW · WASHINGTON, DC 20240

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The interface between invasive species and the increased incidence of tick-borne diseases, and the implications for federal land managers

According to the Centers for Disease Control and Prevention, the incidence of tick-borne disease is on the rise in United States. Annually, there are more than 30,000 reported cases of Lyme's disease alone in the U.S.; and this is believed to be a very low estimate, due to the lack of definitive diagnosis or incorrect diagnose of the disease. The region in which the disease is occurring is expanding every year.

There are many reasons for the increase in tick-borne disease outbreaks including, climate change affecting both, disease vectors and the habitat of vectors and hosts. There is expansion of the range of the various species of ticks which carry specific diseases, expansion in the population and range of wildlife species that serve as reservoirs and hosts for various diseases, changing land use patterns, and a variety of other factors.

There is a significant interface between tick-borne diseases and the diverse issues related to invasive species, since the expansion of the areas affected by various diseases is often facilitated by the movement of vector species, host or reservoir species, and contributory plant species from affected areas into unaffected habitats or regions. Invasive species can include any organism that enters and becomes established in a region to which it is not native, and has a negative impact on the ecosystem. In the case of tick-borne diseases, invasive species which could contribute to the spread of various diseases may include invasive plant species which afford tick vectors with an unnaturally beneficial habitat (such as Japanese Honeysuckle and Japanese Burberry), invasive tick species (including those from outside the United States, such as the Asian Longhorn tick, and species of tick native to one region of the U.S. which are spread to another region), invasive disease hosts (including wildlife species that serve as reservoirs for the diseases of concern), and invasive diseases—those bacterial, viral, or protozoal pathogens which cause tick-borne diseases (such as Lyme's disease, Erlichiosis, Powassn virus, Tickborne encephalitis, Babeiosis).

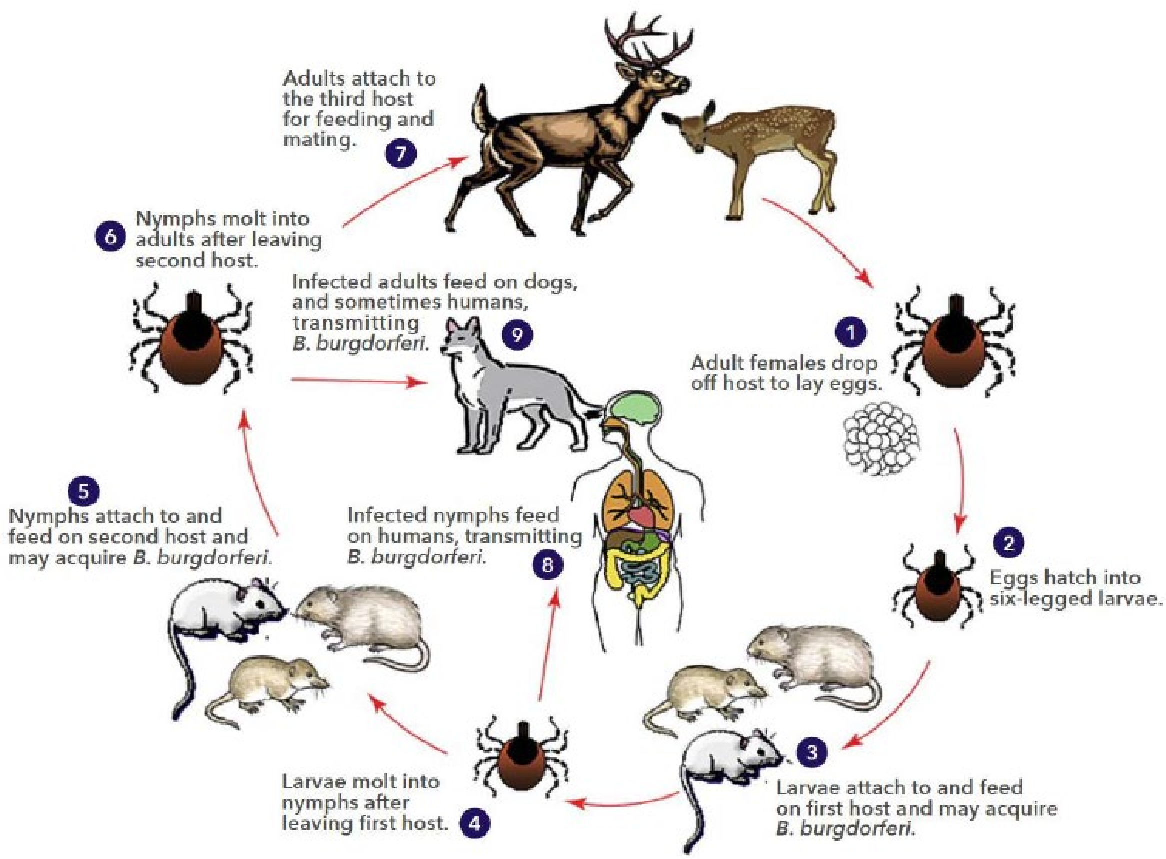
The issue of the increased incidence and severity of tick-borne diseases can be of particular concern to federal land managers in agencies across the government. For the Department of Defense, tick-borne disease is an issue that could adversely affect military personnel, civilian contractors, families of personnel, or other users of these special purpose federal lands, as well as military working dogs and horses, thus having a potentially serious negative impact of the readiness of U.S. armed forces. For managers of national parks, national wildlife refuges, or other public access lands, tick-borne disease which originates in public land units can have a serious adverse impact on public health and safety, the health of agency personnel, environmental health, and local or regional economies.

Therefore, it is incumbent on federal agencies, and especially federal land managers, to understand the dynamic of tick-borne diseases, including the full life cycle of the vector(s) of concern, potential hosts (including domestic animals and wildlife species that may encourage the spread of vectors and any associated pathogens), and the types of habitat in which these disease vectors and their hosts are typically and predictably found. Important aspects of this understanding are and awareness of relevant and timely information sources about the incidence of various diseases, monitoring data on regional distribution of vector tick species, and an awareness of the specific diseases carried by site or region-specific tick population. Once armed with the relevant data, land managers need to acquire the resources and skills to conduct site-specific monitoring techniques to determine the density and diversity of vector ticks on a given federal land unit, and predict the tick-borne disease risk. With current and relevant data, land managers will be better able to make decisions and undertake vegetation or other habitat management activities that can effectively and safely reduce the threat of tick-borne diseases.

The following document is a compendium of reference material related to the interface between invasive species and tick-borne diseases with a particular focus on the implications for federal land managers. Therein the Invasive Species Advisory Council makes a few specific recommendations for relevant National Invasive Species Council member departments (see page 32).

1 – The Life Cycle of Ixodes scapularis ticks and the transmission of Lyme's Disease

Figure 5: *Ixodes scapularis* Tick Life Cycle and the Transmission of Lyme Disease (*Borrelia burgdorferi*)



The tick transmission cycle sustains the bacteria, *B. burgdorferi,* that cause Lyme disease. Lyme disease ... four seasons. Nymphs, ... for transmitting the ma...

2 - The Dynamics of Tick-borne Disease

Throughout the 20th and 21st centuries, the number of infectious diseases in humans has been increasing as approximately 335 human infectious diseases have emerged since 1940 (Jones et al., 2008; Figure 2-1). Approximately 60 percent of those diseases are zoonotic, of which 72 percent are transmitted from wildlife and the remainder are transmitted from domestic animals. Furthermore, approximately 30 percent of emerging infectious diseases are vector-borne, which include tick-borne diseases (TBDs). Currently, there is incomplete and inadequate knowledge about key factors pertaining to persistence of reservoir, transmission, and host responses. More research is needed to better understand these diseases and to improve strategies to protect human health. https://www.ncbi.nlm.nih.gov/books/NBK57013/

Transboundary zoonotic tick-borne diseases can maintain a dynamic focus and have pathogens circulating in geographic regions encircling multiple geopolitical boundaries. Global change is intensifying transboundary problems, including the spatial variation of the risk and incidence of zoonotic tick-borne diseases. The complexity of these challenges can be greater in areas where rivers delineate international boundaries and encompass transitions between ecozones. The Rio Grande serves as a natural border between the US State of Texas and the Mexican States of Chihuahua, Coahuila, Nuevo León, and Tamaulipas. Not only do millions of people live in this transboundary region, but also a substantial amount of goods and people pass through it everyday. Moreover, it occurs over a region that functions as a corridor for animal migrations, and thus links the Neotropic and Nearctic biogeographic zones, with the latter being a known foci of zoonotic diseases. However, the pathogenic landscape of important zoonotic diseases in the south Texas-Mexico transboundary region remains to be fully understood. An international perspective on the interplay between disease systems, ecosystem processes, land use, and human behaviors is applied here to analyze landscape and spatial features of Lyme Borreliosis and human Babesiosis. Surveillance systems following the One Health approach with a regional perspective will help identifying opportunities to mitigate the health burden of those diseases on human and animal populations. It is proposed that the Mexico-US border along the Rio Grande region be viewed as a continuum landscape where zoonotic tick-borne pathogens circulate regardless of national borders. Front Public Health. 2014 Nov 17;2:177. doi: 10.3389/fpubh.2014.00177. eCollection 2014.

In some parts of the world ticks are the most dangerous animals followed by mosquitoes as ectoparasites and vectors of infectious agents, causing morbidity and mortality in domestic animals including wildlife and humans. The majority of tick-borne diseases are zoonotic. The global importance of ticks and tick-borne diseases in veterinary medicine and public health keeps growing. Some ticks are invasive and transmit pathogens causing transboundary diseases of high consequence for populations of domestic animals and humans. Integrated management pursues the optimized use of compatible methods to manage pests in a way that is safe, economically viable, and environmentally sustainable. The area-wide approach augments and expands the benefits of integrated pest management strategies. Issues challenging the implementation, adoption, and viability of area-wide tick management programmes include funding and socio-political aspects, the availability of support systems[RCP1] related to extension and veterinary services, and stakeholder involvement. Management strategies need to adapt and integrate novel technologies to decrease significantly the use of pesticide and address the complex problem of ticks and tick-borne diseases effectively. Applying the “One Health” concept, the strategy to optimize health outcomes for humans, animals, and the environment, facilitates research on the interplay between climate, habitat, and hosts driving tick population dynamics. It enhances our understanding of the epidemiology of tick-borne diseases and advances their management. This overview of research for adaptive area-wide integrated management concentrates on ticks affecting livestock. Examples focus on Rhipicephalus microplus(Canestrini) as one of the tick disease vectors most studied worldwide. Highlights of integrated management research for ticks of public health importance transmitting zoonotic diseases are reviewed to document opportunities for integrated control that mitigate the health burden of tick-borne diseases on humans, domestic animals, and wildlife. Implementation of the research conducted so far, is needed to accelerate advancements in area-wide management of tick populations that can be applied to improve prevention across tick-borne diseases, while decreasing pesticide application and contributing to vector control globally.

3 - Tick-borne Diseases in Human

LANDSCAPE OF LYME DISEASE: CURRENT KNOWLEDGE, GAPS, AND RESEARCH NEEDS

Gary P. Wormser, M.D., New York Medical College

Lyme disease is the most commonly reported vector-borne infection in the United States. B. burgdorferi is the only recognized pathogen to cause Lyme disease in the United States, and can be differentiated into 16 to 45 subtypes that may vary in infectivity and/or in pathogenicity (Wormser et al., 2008a; Crowder et al., 2010). In Europe, B. burgdorferi also causes Lyme disease, but other species of Borrelia, such as Borrelia afzelii and Borrelia garinii, also are responsible for Lyme disease. Because different species are responsible for infection in the two locations, the clinical syndromes associated with Lyme disease also differ between the United States and Europe.

The reported incidence rate of Lyme disease has increased steadily from 10,000 cases in 1992 to approximately 30,000 cases in 2009 (CDC web-site) (Figure 5-1). Twelve states in the Northeast, Mid-Atlantic, and North Central regions of the United States account for nearly 95 percent of these reported cases. New Hampshire (a 37-fold increase) and Maine (a 19-fold increase) have seen the largest proportionate increases in the number of cases during the past 10 years. New York has the largest absolute number of reported cases of Lyme disease, but is only fifth in the incidence of Lyme disease—the number of cases per 100,000 residents. Connecticut has the highest reported incidence.

In the United States, B. burgdorferi are transmitted exclusively by Ixodes ticks, which may transmit pathogens that cause other infections as well, including babesiosis, human granulocytic anaplasmosis, and flavivirus Powassan-like encephalitis. Of the diseases transmitted by I. scapularis, flavivirus Powassan-like encephalitis virus is the least well characterized. One recent study suggested that 2–5 percent of adult Ixodes scapularis ticks collected from two sites in Westchester County, New York, in 2008 contained Powassan virus (Tokarz et al., 2010). Approximately 4 percent of those ticks also contained B. miyamotoi, a relapsing fever-like Borrelia. Whether Borrelia miyamotoi causes human infection is unknown, and the clinical manifestations, if it does, are likewise unknown. Both Powassan virus and B. miyamotoi deserve of additional research efforts.

A number of animals act as reservoirs for Borrelia species, including mice, other small mammals, and some birds. Although deer serve as hosts for Ixodes ticks, they are not competent reservoirs for B. burdorferi. A number of prevention strategies have been demonstrated to decrease the incidence of Lyme disease. Reducing the number of ticks through the use of acaricides on land, mice, or deer is one approach for preventing Lyme disease. Modifying landscapes and building fences to keep deer away from inhabited areas can also reduce human exposure to ticks. Some investigators have reported that simply clearing leaf litter can reduce the number of ticks by approximately 90 percent (Schulze et al., 1995). Personal protective measures have been shown to reduce exposure to ticks. These measures include covering up as much as possible when outdoors, using insect repellents on exposed skin (Vasquez et al., 2008), bathing within 2 hours of tick exposure, and performing daily tick checks (Connally et al., 2009).

Absent from this arsenal of personal protective measures is a human Lyme disease vaccine. A first generation Lyme disease vaccine was introduced in 1998 by GlaxoSmithKline and was approximately 80 percent effective against Lyme disease. The reasons for the withdrawal of the vaccine from the market in 2002 are multifactorial and would be difficult to enumerate in this section. Subsequently, little work has been done to develop a new human vaccine. There is interest in developing a Lyme disease vaccine for mice, because they are the host reservoir for this infection. In laboratory experiments, Borrelia infection rates can be substantially reduced by feeding antibacterial compounds to mice (Dolan et al., 2008). Limiting the pathogen burden in the host reservoir, either through vaccination or antibacterial treatment, would likely reduce the proportion of ticks that become infected and therefore are capable of transmitting Lyme disease to humans. However, the long-term feasibility of such an approach is unknown.

Lyme disease has several stages. Early localized Lyme disease manifests as a single skin lesion known as erythema migrans (EM). Early disseminated Lyme disease consists of multiple erythema migrans skin lesions in addition to possible cardiac and neurological manifestations, such as seventh cranial nerve palsy and meningitis. Late Lyme disease is most often associated with arthritis in large joints, less commonly with neurological and cardiac manifestations, and in Europe, acrodermatitis, a chronic skin condition.

From 1992 to 2006, 248,074 cases of patients with Lyme disease were reported to the U.S. Centers for Disease Control and Prevention (CDC). Of these patients, 69 percent had EM, 32 percent had arthritis, and 12 percent had neurological manifestations (Bacon et al., 2008). In contrast, during a vaccine trial that monitored 267 patients before and after they became ill, approximately 73 percent had erythema migrans, approximately 1.5 percent had arthritis, and 18 percent had developed a nonspecific viral-like syndrome (Steere et al., 1998). Other studies have suggested that 10 percent of patients believed to be infected with B. burgdorferi present with a viral-like syndrome, but the clinical manifestations and patterns of disease progression have not been well characterized (Aucott et al., 2009). Furthermore, approximately 7 percent of individuals in the vaccine trial study developed an asymptomatic infection based on documented seroconversion. At this time, the natural history for asymptomatic infection, and whether it is the same as that for untreated erythema migrans, is unknown. This area needs further study.

In 2008, the CDC/Council of State and Territorial Epidemiologists (CSTE) surveillance case definition for Lyme disease was made more encompassing to allow the documentation and tabulation of other manifestations reportedly associated with Lyme disease. The definition of a confirmed case remained the same: either erythema migrans, or late manifestations of the disease with laboratory evidence of infection. However, a definition for a probable case was added of physician-diagnosed Lyme disease with laboratory evidence of infection using a two-tier test. That is, any disease a physician designates as Lyme disease is a probable case if supported by laboratory test results. In 2009, clinicians reported 8,500 probable cases of infection, for a confirmed-to-probable ratio of 3.5 to 1.

CDC and CSTE also added two definitions for a suspected case: (1) EM with no known exposure to ticks and no laboratory evidence of infection, and (2) laboratory evidence of infection in the absence of clinical information. These changes were a constructive attempt to build the knowledge base regarding the spectrum of illness among persons that the community considers to have Lyme disease.

Current serological testing for Lyme disease presents a number of challenges. First, serology testing using Western blots during early Lyme disease and in patients with erythema migrans is not sensitive. Second, the over-reading of weak bands on a Western blot by many commercial laboratories results in a high percentage of false-positive reports, although no studies have been done to document the percentage. Third, residents of some high-risk regions may demonstrate background seropositivity, leading them to test positive for Lyme disease on IgG Western blots even though they are completely well or have confirmed illness due to other etiologies. In one study, more than 50 percent of individuals who tested positive for Lyme disease on Western blot had no history of having had Lyme disease (Hilton et al., 1999). Finally, there are some patients who, after successful treatment and resolution of early Lyme disease symptoms, maintain persistent antibodies to B. burgdorferi.

Serologic findings lag the presence of erythema migrans. In a study of 252 patients in the United States with erythema migrans, serologic testing, including whole cell sonicate enzyme-linked immunosorbent assay (ELISA), two-tier testing, and the second generation serologic assay, C6 showed low sensitivity during the first 7 days of infection when erythema migrans is present. By 20–30 days after the onset of illness, the frequency of a positive C6 serologic test rises to approximately 100 percent of all patients (Wormser et al., 2008b). Although the dissociation of symptoms and laboratory results may appear insignificant, erythema migrans can resemble southern tick-associated rash illness (STARI), which appears after the bite of a lone-star tick (Amblyomma americanum). In fact, cases of STARI have been reported in Maryland and New Jersey, where B. burgdorferi infection is also common. The ability to differentiate STARI from B. burgdorferi infection clinically and in the laboratory would be helpful. Currently, the etiology, disease burden and patterns, and clinical manifestations (other than a rash) of STARI are unknown.

Borrelia burgdorferi spirochetes are thought to move from the site of a tick bite to other parts of the skin and organs through hematogenous dissemination. Blood cultures of approximately 40 percent of untreated patients in one study, tested up to 1 month after erythema migrans first appeared, yielded B. burgdorferi regardless of the size or duration of the rash (Wormser et al., 2005).

Approximately 73 percent of Lyme disease patients have symptoms in addition to a skin lesion when they first seek treatment, including arthralgias (joint pain), myalgias (muscle pain), fatigue, malaise, neck pain, and headache. Approximately 25 percent of patients continue to report milder symptoms even after treatment, although their skin lesions have long since resolved. The median frequency of reported symptoms at 6 months is approximately 11.5 percent in eight U.S. randomized treatment trials (Cerar et al., 2010).

Three long-term outcome studies of patients with Lyme disease found that among healthy controls, who did not have Lyme disease, 15–43 percent reported fatigue, 16–20 percent reported headaches, up to 27 percent reported joint pain, and 19 percent reported muscle aches. These findings call into question whether the percentages of Lyme disease patients who continue to have symptoms more than 6 months after treatment exceed the percentages of the general population reporting the same symptoms. Furthermore, if the percentages among those reported to have Lyme disease are above the background rates, the causes of the long-term symptoms among Lyme disease patients remain unknown. A number of factors are associated with long-term symptoms, including how severely ill patients are when they first seek care (Nowakowski et al., 2003), the presence of neurologic manifestations (Eikeland et al., 2011), prior or current psychiatric conditions (Solomon et al., 1998), and greater sensitivity to symptoms (i.e., patients who are more aware of their symptoms will report them over a longer length of time). There are limited data suggesting that coinfection with untreated babesiosis and autoimmune events, such as the production of antineural antibodies, are correlated with long-term symptoms.

Some of the controversies surrounding Lyme disease reflect the fact that the disease means different things to different people. To some, Lyme disease is insidious and ubiquitous: Such patients commonly present with nonspecific symptoms, are diagnosed based on clinical judgment because diagnostic tests are insensitive, and require antibiotic treatment for months to years. To others, Lyme disease occurs focally, depends on exposure to infected ticks, and usually is linked to objective clinical manifestations. Positive laboratory tests are needed to support a diagnosis for symptoms other than EM, and the disease typically responds to antibiotic treatment.

Resources:

https://www.cdc.gov/ticks/geographic_distribution.html
https://www.cdc.gov/ticks/tickbornediseases/index.html
https://www.cdc.gov/ticks/tickbornediseases/overview.html

4 – Tick-borne Diseases in Domestic Animals

Assessing the risks associated with vector-borne pathogens relies on multiple factors, including understanding the distribution of important vector species. Determining the characteristics of vector populations in a region can involve assessing the current distribution, expected changes in distribution, abundance, host associations, host density, and suitable environmental conditions (Burkett-Cadena et al 2013). However, for many vector-borne diseases (VBD), the presence of a vector species in an area is not the single factor in the determination of the risk for infection to livestock or equines. The prevalence and seasonal activity of vector-borne diseases are influenced by a number of other factors such as climate, vector/host presence, availability of hosts, landscape characteristics, land-use, animal management practices, and human behavior (Mansfield et. al 2017).

Vector presence can be an indication of the transmission of vector-borne disease as we observe with the black-legged tick and Lyme disease in the northeastern part of the United States. However, vector presence does not always indicate the presence of disease, as we observe the presence of cattle fever ticks in South Texas, with no accompanying cattle tick fever (babesiosis) (Eisen et al 2016, deLeon et al 2012). Climate will influence the seasonality and the location of vectors and thus potential exposure of livestock and equines to a vector-borne disease will vary with changes in weather patterns (Paz 2015).

Non-climate factors will also affect the presence of a vector-borne disease in an area such as livestock outdoor exposure, efficacy of tick control products, vaccine usage, human behavior, and proximity to vector habitat (Kilpatrick and Randolph 2012). The majority of equine piroplasmosis cases in the United States are a result of the use of needles being shared between infected horses {USDA, 2009 #85}.

Therefore, livestock populations may be affected differently by a vector-borne disease depending on changes in climate, vector distributions, landscape, and animal management practices. All of these factors are important in maintaining enzootic vector-borne disease cycles {Sonenshine, 1991}. Monitoring vector populations that infest domesticated and wild animal species is an essential component to providing reliable, standardized, and consistently good quality datasets not only for disease risk assessments, but also for early detection of vector-borne disease outbreaks, prevention, control, and managing vector-borne diseases in the United States {Dorea, et al. 2016; USDA, 2014 #67}.

The risk for vector-borne diseases in the United States is highly geographically diverse with an assortment of vector(s) and livestock species affected on a seasonal basis. Veterinary Services has more than 25 vector-borne diseases of concern (Table 1). If we consider that West Nile virus has been detected in more than 65 mosquito species alone {Colpitts, 2012 #99} {CDC, 2012) then the list of potential vector species (including ticks, mosquitoes, midges, and other biting flies) that might transmit a pathogen to livestock is extensive.

5 – Tick-borne diseases and wildlife

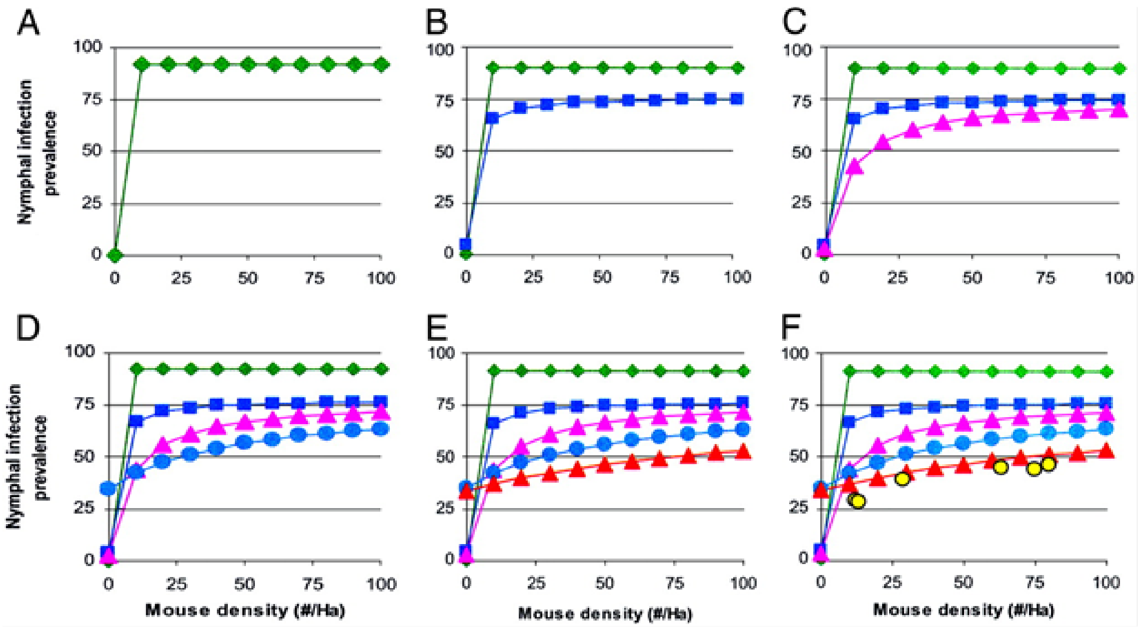
Abstract: Forest destruction and fragmentation in the United States recently have been shown to reduce mammalian species diversity and to elevate population densities of white-footed mice (Peromyscus leucopus). One potential consequence of reduced species diversity and high mouse density in small fragments is an increase in human exposure to Lyme disease. Increased risk of exposure to this disease is expected because of the role of the white-footed mouse as the principal natural reservoir of the Lyme bacterium, Borrelia burgdorferi. Blacklegged ticks (Ixodes scapularis) feeding on mice have a higher probability of becoming infected with the bacterium than do ticks feeding on any other host species. We hypothesized that small forest patches (<2 ha) have a higher density of infected nymphal blacklegged ticks, which is the primary risk factor for Lyme disease, than larger patches (2–8 ha). In the summer of 2000, we sampled tick density and B. burgdorferi infection prevalence in 14 maple-dominated forest patches, ranging in size from 0.7 to 7.6 ha, in Dutchess County of southeastern New York state. We found a significant linear decline in nymphal infection prevalence with increasing patch area and a significant exponential decline in nymphal density with increasing patch area. The consequence was a dramatic increase in the density of infected nymphs, and therefore in Lyme disease risk, with decreasing forest patch size. We did not observe a similar relationship between the density of larval ticks and patch size. These results suggest that by influencing the community composition of vertebrate hosts for disease-bearing vectors, habitat fragmentation can influence human health.

The inexorable loss of species from ecological communities is a worldwide phenomenon that has prompted ecologists to critically examine the relationship between biodiversity and ecosystem function. Diversity has been causally linked to many ecosystem characteristics including productivity variability, resilience, and resistance to invasion and stressors, Here, we present evidence that diversity, in the form of species richness, can play an important role in determining disease risk to humans, using Lyme disease as a model system. Lyme disease (etiologic agent Borrelia burgdorferi), the most common vector-borne disease in North America, is transmitted by ticks of the family Ixodidae. We tested the Dilution Effect model, which predicts that high species diversity in the community of hosts for ticks reduces the infection prevalence of ticks by diluting the effects of the ubiquitous white-footed mouse (Peromyscus leucopus), the principal natural reservoir for B. burgdorferi.

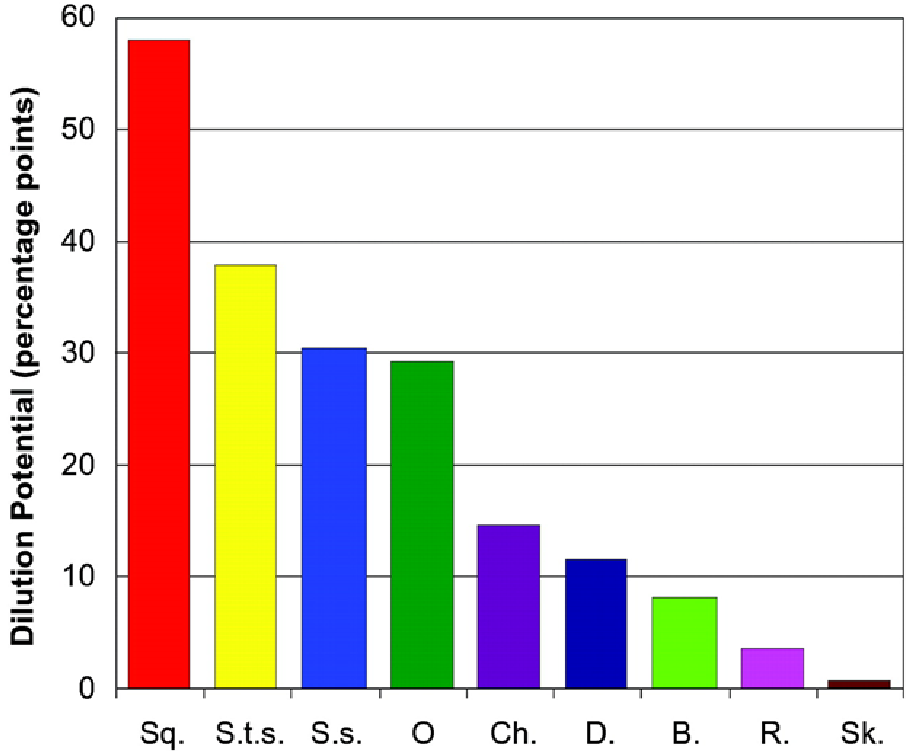
In the forests of eastern North America, the immature stages of the Lyme disease vector, Ixodes scapularis, are extreme generalists, feeding on numerous mammalian, avian and reptilian host species, most of which are believed or documented to have low reservoir competence. The white-footed mouse, which infects from 40% to 90% of the larval ticks that feed on it, has wide habitat tolerances, occurring in pristine forest as well as in degraded woodlots. Therefore, species-poor communities tend to have mice, but few other hosts, whereas species-rich communities have mice, plus many other potential hosts, which should dilute the impact of mice by feeding but rarely infecting ticks. The resulting expectation, the Dilution Effect hypothesis, is decreasing infection prevalence in the tick population with increasing host diversity. The Dilution Effect might not be a "pure" diversity effect, but could result from the observed correlations among vertebrate diversity and relative abundances of pathogen-carrying host species.

Of the three postegg life stages of the tick, the nymphal stage is most likely to infect humans. Because there is no transovarial transmission, the host from which the larval blood meal is taken is a key predictor of whether a nymph will be infected with B. burgdorferi. We use nymphal infection prevalence (NIP) as a measure of disease risk to humans and, by extending and parameterizing the model of Giardina et al. , investigate the change in NIP as the diversity of the host community is increased. NIP represents the probability of being exposed to Lyme bacteria if bitten by a nymphal tick and is a function of the distribution of larval meals among the community of vertebrates. The importance of NIP is well demonstrated in the varying prevalence of B. burgdorferi in North American ticks. Although I. scapularis occurs throughout the eastern half of the United States, B. burgdorferi prevalence is low in southern states and cases of Lyme disease are correspondingly low in these areas. Thus, despite high vector densities, disease risk to humans can be quite low if vector infection prevalence is also low.

Some common tick hosts serve not only to dilute the effects of the most competent reservoirs, but also to maintain the spirochete in the community under conditions of low mouse density For example, in the most diverse community, NIP is predicted to be 34%, even at 0 mice per hectare (Fig. 1E). This is largely due to the effects of shrews, which have high reservoir competence, provide meals for many ticks, and can occur at high densities.



Predicted NIP across a realistic range of mouse densities as host diversity is increased and host community composition is concomitantly changed. Host community consisting of only white-footed mice (green diamonds) (A); white-footed mice, chipmunks, and white-tailed deer (dark blue squares) (B); all hosts in B plus raccoons, opossums, and skunks (pink triangles) (C); all hosts in C plus short-tailed shrews and four species of ground nesting birds (light blue circles) (D); all hosts in D plus tree squirrels and Sorex shrews (red triangles) (E); and field data collected at our site over 7 years, showing the mouse density during the larval peak in year t and NIP for host-seeking nymphs in year t + 1 (yellow circles) (F).



The ability of each species to reduce the effect of white-footed mice (the most competent reservoir) on NIP. Dilution potential is the difference (in percentage points) between the expected NIP in a two-host community consisting of mice plus the focal species and a community in which mice are the only possible host. Sq., squirrel; S.t.s., short-tailed shrew; S.s., Sorex shrew; O, opossum; Ch., chipmunk; D, deer; B, birds; R, raccoon; Sk, skunk.

Tree squirrels [gray squirrels (Sciurus carolinensis) and red squirrels (Tamiasciurus hudsonicus) combined] have the highest dilution potential, reducing infection prevalence by ≈58% points from what it would be if ticks were feeding on mice alone. Other hosts occur at too low densities [e.g., skunks (Mephitis mephitis)] and/or host too few ticks (e.g., birds) to function as effective dilution hosts.

The Dilution Effect may provide incentive to maintain high diversity and stable community composition through wise land-use practices. For example, forest fragmentation decreases mammalian biodiversity and results in areas of very high mouse density, which this model predicts would represent the highest Lyme disease risk.

Reference: The ecology of infectious disease: Effects of host diversity and community composition on Lyme disease risk. Kathleen LoGiudice, Richard S. Ostfeld, Kenneth A. Schmidt, FeliciaKeesing. Proceedings of the National Academy of Sciences. Jan 2003, 100 (2) 567-571

Babesiosis is an emerging zoonotic disease on all inhabited continents and various wildlife species are the principal reservoir hosts for zoonotic Babesiaspecies. The primary vectors of Babesia are Ixodid ticks, with the majority of zoonotic species being transmitted by species in the genus Ixodes. Species of Babesia vary in their infectivity, virulence and pathogenicity for people. Various factors (e.g., increased interactions between people and the environment, increased immunosuppression, changes in landscape and climate, and shifts in host and vector species abundance and community structures) have led to an increase in tick-borne diseases in people, including babesiosis. Furthermore, because babesiosis is now a reportable disease in several states in the United States, and it is the most common blood transfusion-associated parasite, recognized infections are expected to increase. Because of the zoonotic nature of these parasites, it is essential that we understand the natural history (especially reservoirs and vectors) so that appropriate control and prevention measures can be implemented. Considerable work has been conducted on the ecology of Babesia microti and Babesia divergens, the two most common causes of babesiosis in the United States and Europe, respectively. However, unfortunately, for many of the zoonotic Babesia species, the reservoir(s) and/or tick vector(s) are unknown.

In the eastern US, where the incidence of human babesiosis is highest, the primary reservoir is the white-footed mouse (Peromyscus leucopus) (Anderson et al., 1991, Telford and Spielman, 1993, Stafford et al., 1999). However, infections with morphologically similar Babesia have been reported in other rodents that are sympatric with P. leucopus (e.g., meadow voles (Microtus pennsylvanicus), short-tailed shrews (Blarina brevicauda), brown rats (Rattus norvegicus), Eastern cottontail rabbits (Sylvilagus floridanus), and Eastern chipmunks (Tamias striatus)) (Healy et al., 1976, Spielman et al., 1981, Anderson et al., 1986, Anderson et al., 1987, Telford et al., 1990). In general, prevalences in reservoir hosts are high (>25%) (Healy et al., 1976, Spielman et al., 1981, Anderson et al., 1986). A recent study by Hersh et al. (2012), described the reservoir competence for a suite of potential hosts by collecting engorged I. scapularis larvae and testing resulting nymphs for B. microti. Two strains of B. microti were detected in the nymphs, one was a strain associated with human infections, but the other was genetically unique and only found in nymphs from opossums(Didelphis virginiana), raccoons (Procyon lotor), and a single wood thrush (Hylocichia mustelina). For the B. microti strain associated with human infections, the white-footed mouse had the highest reservoir competence (average of 29.5% of ticks became infected) followed by short-tailed shrews and eastern chipmunks (averages of 21.9%, and 17.6%, respectively). Interestingly, masked shrews (Sorex cinereus) also infected a high percentage of ticks, but only a limited number of ticks and hosts were tested.

In Maine, where I. scapularis is absent or rare, a B. microti that was genetically distinct from human-infecting strains was detected in a redback vole(Clethrionomys gapperi), a masked shrew (S. cinereus), and a short-tailed shrew (Goethert et al., 2003). Interesting data from England and Japan suggest that shrews (Sorex spp.) are important hosts; however, few studies have been conducted on US Sorex spp. (Burkot et al., 2000, Goethert et al., 2003, Zamoto et al., 2004b, Bown et al., 2011) Many of these B. microti reservoirs are also competent reservoirs for two other zoonotic pathogens, Borrelia burgdorferiand Anaplasma phagocytophilum, so coinfections of reservoirs and ticks are common (Magnarelli et al., 2006, Abrams, 2008, Tokarz et al., 2010). Experimental or field-based studies are needed to better understand the reservoir competence of rodent species for B. microti in the Northeastern US.

Infections with B. microti, based on either morphology or PCR analysis, have been reported in rodents in the western and southeastern US where B. microti-associated human babesiosis is not known to be endemic. Recently, a high prevalence of B. microti (genetically similar to human-associated strains) was detected in cotton rats (Sigmodon hispidus) in Florida (Clark et al., 2012). In Alaska, B. microti (genetically distinct from human-associated strains) has been detected in Northern red-backed voles (Myodes (Clethrionomys) rutilus), tundravoles (Microtus oeconomus), singing voles (Microtus miurus), shrews (Sorex spp.), and Northwestern deer mice (Peromyscus keeni) (Goethert et al., 2006). In Colorado, B. microti was identified in 13 of 15 prairie voles (Microtus ochrogaster) by PCR of blood or spleens (Burkot et al., 2000). Similarly in Montana, nearly half of all montaine voles (Microtus montanus), meadow voles, and water voles (Arvicola richardsoni) tested by blood or spleen smears were infected with B. microti, whereas none of 40 deer mice (Peromyscus maniculatus) were infected (Watkins et al., 1991). Uncharacterized Babesia spp. have been detected in rodents from Wyoming and California (Wood, 1952, van Peenen and Duncan, 1968, Watkins et al., 1991). B. microti from microtine rodents in Alaska are phylogenetically related to strains detected in other rodent species in Montana and Maine, but these parasites were distinct from human-associated B. microti strains from the United States, Asia, and Europe (Goethert et al., 2006). Therefore, the finding of B. microti (based on morphology) in rodents in a particular geographic area might not suggest a high risk of human infection. As additional evidence that genetic characterization is needed, a small piroplasm from dusky-footed woodrats (Neotoma fuscipes) in California was shown to be a Theileria species (Kjemtrup et al., 2001).

6 - Matrices of ties between habitat, human activities, and ticks

Understanding complex tick-borne pathogen systems and responding to the urgent human health threat requires coordinated multidisciplinary research and management efforts across broad geographic areas and over long time periods (Rohr et al. 2010, Léger et al. 2013, Estrada-Pena et al. 2014, Ostfeld and Brunner 2015, Kilpatrick et al. 2017). Ticks, such as *Ixodes scapularis*, are part of complex disease systems that include multiple pathogens, life-stage-specific hosts, forest habitat characteristics, interactions across trophic levels, and climatic drivers (Figure 1). Ticks acquire pathogens during blood meals of competent hosts or less-commonly by transovarian spread. The likelihood of a pathogen transmission depends upon host community composition. Host communities, in turn, are influenced by habitat, predation, and resource availability.

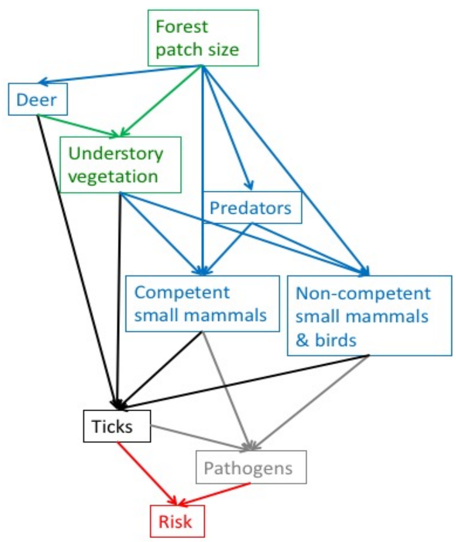


Figure 1. A simplified, general tick-borne-pathogen system conceptual model showing key direct and indirect influences among system components, including habitat and vegetation (green), host (blue), vector (black), pathogens (gray), and human risk (red).

Alternate figure from Ostfeld et al Ecology, 99(7), 2018, pp. 1562–1573

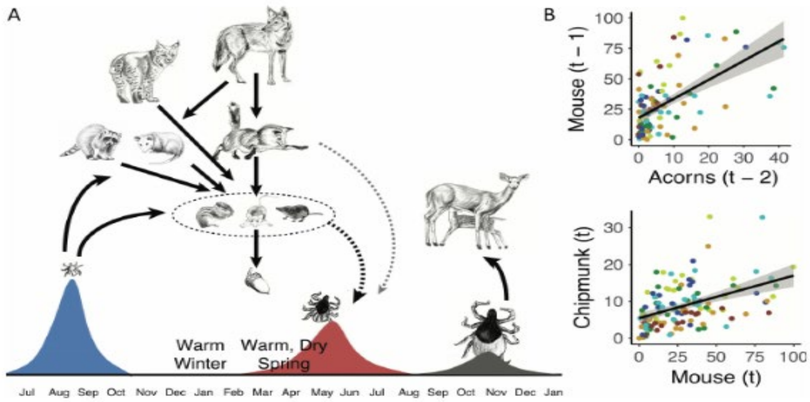


FIG. 1. Tick life cycle (A) in the context of the food web and climate, and (B) highlighting bottom-up forcing of mice and chipmunks by correlation, via the size of the previous year acorn crop. Results from each of six grids are separated by color. Drawings by Yiwei Wang and Taal Levi.

Human activities can therefore influence tick borne disease risks on the landscape through several mechanisms. Human development results in increased forest fragmentation and decreased forest patch size, which in turn dramatically influences community composition in these remnant forests. Human activities have also influenced predator and community composition, resulting in complete removal of apex predators (ie, red wolves, mountain lions) and significant impacts to mesopredators in eastern forests, which in turn affects population densities of the primary blood meal hosts of ticks in eastern forests, white-tailed deer and *Peromyscus* species. Human activity has also resulted in the introduction of invasive plant species that have been shown to dramatically influence tick density and infection prevalence (Lubelczyk et al. 2004, Elias et al. 2006, Williams and Ward 2010).

<u>Per Doug Burkett</u>:

Alien invasive plants can serve a significant role and likely enhance tick, host and tick-borne pathogen survival and distribution. Exotic plants often invade areas of high human activity, such as along trails, roads, and forest edges, and in disturbed riparian areas. These same habitat types are also favored by ticks, tick hosts and the pathogens they carry.. This convergence suggests that habitat modifications caused by exotic plant invasions may mediate disease vector habitat quality, indirectly affecting human disease risk at the local spatial scale. For those few species that have been evaluated, some alien invasive plant species are more important tick refugia than others. Forest understories are subject to invasion by exotic vegetation such as honeysuckle (Miller and Gorchov 2004) and multiflora rose (Adalsteinsson et al. 2016). These species form dense groves which provide suitable microclimate conditions for I. scapularis (Lubelczyk et al. 2004, Christopher and Cameron 2012) and abundant fruit and cover for wildlife.

Elias et al. 2006 found twice as many adult ticks (*Ix. scapularus*) and nearly twice as many nymphs in plots dominated by exotic-invasives than in plots dominated by native shrubs. Both adult and nymphal counts were lowest in open understory with coniferous litter. Adults were positively associated with increasing litter depth, medium soil moisture, and increasing abundance of white-footed deer mice, *Peromyscus leucopus*, and deer pellet group counts. Nymphs were positively associated with increasing litter depth, moderately wet soil, and mice. We concluded that deer browse-resistant exotic-invasive understory vegetation presented an elevated risk of human exposure to the vector tick of Lyme disease.

Racelis et al 2012 found *Arundo donax* infestations present environmental conditions that facilitate the survival and persistence of cattle ticks, as well or better than native habitats and open grasslands representing an alarming complication for cattle fever tick management in the United States.

Allan et al 2010 demonstrated that a widespread invasive shrub in North America, Amur honeysuckle (*Lonicera maackii*), increases human risk of exposure to ehrlichiosis, an emerging infectious disease caused by bacterial pathogens transmitted by the lone star tick (*Amblyomma americanum*). Using observational surveys in natural areas across the St. Louis, Missouri region, they found that white-tailed deer (*Odocoileus virginianus*), a preeminent tick host and pathogen reservoir, more frequently used areas invaded by honeysuckle. This habitat preference translated into considerably greater numbers of ticks infected with pathogens in honeysuckle-invaded areas relative to adjacent honeysuckle-uninvaded areas. Author confirmed this biotic mechanism using an experimental removal of honeysuckle, which caused a decrease in deer activity and infected tick numbers, as well as a proportional shift in the blood meals of ticks away from deer. Authors concluded that disease risk is likely to be reduced when honeysuckle is eradicated, and suggest that management of biological invasions may help ameliorate the burden of vector-borne diseases on human health.

Lubelczyk et al. 2004 also found Japanese barberry and honeysuckle to enhance tick abundance (Ix scapularus). The authors concluded that natural resource managers should be aware that landscape changes, including the invasion by exotic vegetation, might create favorable tick habitat and that the findings could prove helpful in assessing local risk of exposure to this vector tick.

The invasive Japanese barberry has been proven to enhance tick, host and Lyme disease pathogen densities and that barberry control significantly reduces tick populations and infection prevalence. Williams et al. 2009 found that eastern forests with an overabundance of white-tailed deer, Japanese barberry (*Berberis thunbergii*) has become the dominant understory shrub, which may provide a habitat favorable to blacklegged tick (*Ixodes scapularis*) and white-footed mouse (*Peromyscus leucopus*) survival. To determine mouse and larval tick abundances at three replicate sites over 2 years, mice were trapped in unmanipulated dense barberry infestations, areas where barberry was controlled, and areas where barberry was absent. Total mouse counts did not differ between treatments. Mean number of feeding larval ticks per mouse was highest on mice captured in dense barberry. Adult tick densities in dense barberry were higher than in both controlled barberry and no barberry areas. Ticks sampled from full barberry infestations and controlled barberry areas had similar infection prevalence with B. burgdorferi the first year. In areas where barberry was controlled, infection prevalence was reduced to equal that of no barberry areas the second year of the study. Results indicate that managing Japanese barberry will have a positive effect on public health by reducing the number of B. burgdorferi (Lyme disease) infected blacklegged ticks that can develop into motile life stages that commonly feed on humans.

Not all invasive species in the understory are proving to enhance tick populations. For example, Civitello et al. 2008 tested whether Japanese stiltgrass, *Microstegium vimineum* altered microclimate conditions and enhanced tick survival. Microstegium is an exotic annual grass that is highly invasive throughout the eastern United States where the vector ticks *Amblyomma americanum* (Linnaeus) and *Dermacentor* *variabilis* (Say) occur. For this particular species where ticks were introduced into experimentally invaded and native vegetation control plots, *D. variabilis* mortality rate increased 173% and A. americanum mortality rate increased 70% in the invaded plots relative to those in control plots. Microstegium invasion also resulted in a 13.8% increase in temperature and an 18.8% decrease in humidity, which are known to increase tick mortality. The authors predicted that areas invaded by Microstegium would have lower densities of host-seeking ticks and therefore reduced human disease risk. Our results emphasize the role of invasive species in mediating disease vector populations, the unpredictable consequences of biological invasions, and the need for integrative management strategies that can simultaneous address exotic plant invasions and vector-borne disease. For Japanese stiltgrass, tick numbers were lower than for native vegetation.

Morlando et al. 2012 concluded that although habitat restoration to native species is expensive, a cost benefit analysis shows that restoration such as removal of invasive trees reduces the LD risk by ~98%. Cost-of-illness studies show that the restoration would be financially justifiable if it averted 75 cases of LD per year. Given the local LD rate and the visitation rate to federal and military lands, habitat restoration can plausibly be justified solely on the benefit of LD cases averted.

Surprisingly, fire management using prescribed burns has been found to have an unintended consequence of increasing tick densities in areas recently burned. Allan et al. 2009 found that the increasingly widespread use of prescribed burns to manage oak (*Quercus spp*.)-hickory (*Carya spp*.) forests in the Missouri Ozarks, USA, has considerable potential to alter the abundance of *Amblyomma americanum* (L.) (Acari: Ixodidae), the lone star tick, an important vector of several emerging pathogens. In particular, responses of important tick hosts, primarily white-tailed deer (*Odocoileus virginianus*), to fire management and the resultant changes in the distribution and abundance of A. americanum are largely unknown. Using several large burn units (61–242 ha) within the Ozark ecosystem, I measured the effect of the time elapsed since sites were burned on the density of white-tailed deer and the larval life stage of *A. americanum*. Larval tick densities were highest in areas that were 2 yr postburn and were >6 times higher than tick densities in control units. Deer densities were highest in sites that were burned in the same year as this study and decreased significantly with time since burn. These results suggest that intensive use of postburn sites by white-tailed deer may increase the abundance of A. americanum to levels greater than occurs in sites that remain unburned. Thus, fire management, although beneficial in many aspects of ecosystem management, may bear the unintended cost of locally increasing abundance of A. americanum.

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7 – Anthropogenic controls on tick populations

The incidence and distribution of Lyme disease and other reportable tick-borne illnesses are increasing across the United States, with over 300,000 new cases of Lyme disease alone occurring each year. In the absence of a vaccine in the U.S. against any of the tick-borne diseases, effective primary prevention relies on reducing exposure to ticks. Identifying and validating effective prevention and control strategies is critical for reducing the incidence of new cases. Additionally, in order to track the effectiveness of national prevention and control strategies, it is essential to maintain an accurate understanding of current disease burden and trends against which to measure success of national prevention goals once established.

Major challenges – disease vectors. In recent decades, the distribution of the important tick vectors of human and animal illnesses have increased steadily and significantly. The number of counties in the U.S. where *Ixodes scapularis*, the vector for Lyme disease, anaplasmosis, babesiosis, and Powassan virus disease, is now established has doubled in the last 20 years (Eisen, Eisen, & Beard, 2016). The reasons for the increase in tick distribution are complex and vary by region. Additionally, due to the lack of a coordinated national tick vector surveillance program, there are significant gaps in information on local distribution of tick vectors, information which is badly needed for educating the public health community, healthcare providers and the general public about local disease risk. Some additional concerns about tick vectors that have arisen over the last two decades include the emergence of *Rhipicephalus sanguineus* as a vector of Rocky Mountain spotted fever in the Southwest, the expansion of *Amblyomma americanum* up the eastern seaboard, and the increase in human host preference of nymphal *Ixodes scapularis* populations expanding southward through Maryland, Virginia, and into the Carolinas, and Tennessee. Additionally, there is a need to better understand the pathogens and vectors associated with tick-borne diseases in the southern states and along the Pacific Coast, and there are concerns about the risk of introduction of exotic tick species such as *Haemaphysalis longicornis,* which was recently identified in New Jersey.

Major challenges – surveillance. Currently seven tick-borne diseases are nationally notifiable in the U.S. In 2016, Lyme disease was the most common vector-borne disease reported and the sixth most common of all nationally notifiable diseases. While approximately 35,000 cases of Lyme disease are reported each year to the CDC, recent studies indicate that the actual number of annual cases exceeds 300,000 (Hinckley et al., 2014; Nelson et al., 2015). Under-reporting is a common phenomenon for most high-incident diseases, and Lyme disease under-reporting is further complicated by a case definition that requires both laboratory and supportive clinical data for confirmation of all but the earliest manifestations of the illness. National disease reporting, while coordinated by CDC, is formally a responsibility of state governments through the Council of State and Territorial Epidemiologists (CSTE). CSTE determines, through votes of its membership, which diseases are nationally-notifiable and the specifics of case definitions. The resulting data are submitted to CDC where the information from each state is collated and made available nationally. Accurate and up-to-date incidence data for all tick-borne diseases, including Lyme disease, are critical in order to demonstrate the burden of illness in terms of both economic cost and human suffering, to establish baselines against which to measure prevention efforts and to monitor disease emergence in new geographic areas. Under-reporting and inconsistencies in surveillance data from state to state and from year to year significantly hamper efforts to raise public awareness of the magnitude of the problem and provide data needed to evaluate prevention effectiveness.

Major challenges – prevention. Currently, no vaccines are available in the U.S. against any tick-borne disease. Consequently, primary prevention relies on methods focused on reducing exposure of people to infected ticks. The toolbox of methods and products available to protect against biting ticks contain such things as personal repellants, acaricides approved for use on people, animals, and properties, landscape management, and personal protective behaviors and actions. The available data to show that any of the tools when deployed as directed can actually prevent human illness is very limited (Connally et al., 2009b). New methods and products are badly needed as well as controlled field trials that measure epidemiologic outcomes in order to provide data-driven prevention recommendations. Additionally, the internet is all too often an easily available source of misinformation, directing those at risk to prevention methods that are ineffective and potentially harmful.

Evidence and Findings

Preventing human-tick encounters can be approached in several ways. Personal protection strategies like performing tick checks or wearing tick repellent are simple to perform and inexpensive, but require daily practice to be most effective. Household-level/peridomestic (backyard) actions, on the other hand, like residential acaricide applications or landscape modifications may require more effort and cost, but require less frequent practice and individual vigilance. Finally, community-level interventions, such as deer management, community-scale tick management, and educational programming, have the potential to make maximum impact on tick populations or disease reduction; these interactions, however, may require widespread public acceptance and may also be limited by municipal or state regulations as well as by manpower required to sustain these efforts.

Personal protective measures. Personal prevention tactics are aimed primarily at shielding the body from tick bites or making ticks easier to detect and remove. Such measures include tucking pants into socks, wearing insect/tick repellent, wearing light colored clothing, performing daily tick checks, bathing frequently, and drying clothes on high heat. Several studies have evaluated the use of personal protective measures for preventing Lyme disease. Many such studies, due to the difficulties in conducting rigorous and meaningful studies, lack data to evaluate their effect for actually preventing human-tick encounters. However, there are a few personal protective measures, including the use of skin and clothing repellent, and performing tick checks and frequent bathing, that have compelling evidence to show they may offer some level of protection against human tick bites and disease.

Skin repellent. Laboratory evaluation of skin repellents suggest that products containing synthetic compounds like 20% or greater DEET, IR3535, picaridin, and synthetic oil of lemon eucalyptus (also known as p-menthane-3,8-diol or PMD), are effective for repelling ticks (Eisen & Dolan, 2016). Several studies have aimed to evaluate repellent use for protecting humans from tick bites and a few have had a protective effect. Studies have demonstrated that an effective repellent applied to skin can protect against Lyme disease (Schwartz & Goldstein, 1990; Vazquez et al., 2008) and was protective against bites from *Ixodes ricinus* ticks in Sweden (Gardulf, Wohlfart, & Gustafson, 2004).

Increased public demand for botanically-based "natural" repellents has led to mass commercialization of products that do not require EPA-registration and so may be labeled with claims of tick repellent effects with little or no data to support these claims. While, some botanically-based compounds and essential oils, such as geraniol, Chinese juniper oil, and intermedeol, do provide some repellent effects against certain tick species in the laboratory trials, most have short durations of repellent effect (Eisen & Dolan, 2016). In addition, active ingredients commonly found in natural tick repellents such as red cedar oil, soybean oil, and peppermint oil, have little or no published data supporting their use for repelling ticks. However, there is one botanical extract found in grapefruit skin and Alaskan yellow cedar called nootkatone that shows particular promise for preventing tick bites. It has demonstrated repellent properties against blacklegged ticks (Dietrich et al., 2006), is safe and commonly used in food and fragrances, and can be mass produced using a yeast fermentation process. In 2017, CDC entered into a licensing agreement with the biotech company Evolva, to further develop nootkatone as an active ingredient in commercially available repellent products such as repellent soaps and lotions to repel vector mosquitoes. Creating safe formulations of nootkatone, has great potential for effective tick bite prevention in the form of soap, lotion, shampoo, or spray for consumer use.

In general, skin repellents can offer a first line of personal protection against tick bites and several compounds have been identified that effectively repel ticks. Barriers to adopting repellent use should be evaluated. Furthermore, despite increased public interest in using natural products as tick repellents (Gould et al., 2008a), studies evaluating natural products specifically for preventing human-tick encounters or tick-borne diseases are mostly lacking from the scientific literature.

Protective clothing. Clothing that has been treated with permethrin insecticide has shown to protect humans from bites from blacklegged ticks in a laboratory setting (Miller, Rainone, Dyer, González, & Mather, 2011) and from lone star tick bites among outdoor workers in North Carolina (Vaughn et al., 2014). Laboratory testing factory-impregnated permethrin-treated clothing has shown that treated clothing kills and repel blacklegged ticks (Eisen, Rose, et al., 2017). Multiple studies of permethrin-treated military uniforms support the use of permethrin-treated clothing as an effective repellent and/or killing multiple tick species (Evans, Korch, & Lawson, 1990; Fryauff, Shoukry, Wassef, Gray, & Schreck, 1998; Schreck, Mount, & Carlson, 1982; Schreck, Snoddy, & Spielman, 1986).

Permethrin-treated clothing has also been shown to have repellent and toxic effects on Pacific coast ticks and Western blacklegged ticks (Lane & Anderson, 1984). Overwhelming evidence suggests that permethrin-treated clothing holds promise as an effective tool for personal protection against tick bites. Unfortunately, its adoption may be limited by public aversion to use of synthetic chemicals as repellents and insecticides (Reid, Thompson, Barrett, & Connally, 2013). Prospective analysis of permethrin-treated clothing on humans for tick bite prevention is warranted and may best be achieved with concomitant study regarding reducing barriers to adopting the use of treated clothing.

Besides treating clothing with pesticide, residents of tick-endemic regions can wear long pants and light colored clothing and they can also tuck pants into socks and shirts into pants. These practices are aimed at preventing ticks from crawling under pant cuffs and by making ticks easier to detect and remove before they can attach to skin. A chemical-free line of clothing was recently developed to be worn under clothing and is meant to protect from tick and insect bites using a tight nylon and Lycra fabric weave with elastic cuffs. It is commonly marketed to sportsmen, law enforcement, and military users. Studies evaluating this clothing for preventing tick bites are thus far lacking, but the clothing has been worn in vector ecology studies for the prevention of arthropod bites by field researchers (Beck, Zavala, Montalvo, & Quintana, 2011).

Tick checks and bathing. Performing bodily inspections for crawling and attached ticks ("tick checks") has been shown to protect against human disease (Connally et al., 2009a; Vázquez et al., 2008). In addition, bathing or showering after spending time outdoors has shown to increase the probability of finding a tick (Mead et al., 2017) and decrease the likelihood of getting Lyme disease (Connally et al., 2009). Although best practices for effective showering/bathing and tick-checking behavior for disease prevention have yet to be established, these activities are inexpensive preventative measures that can be conducted after spending time in any outdoor environment (not just one's own backyard), and should continue to be promoted as essential components of any tick-borne disease prevention program. It is also possible that the additional use of a repellent soap (for example, nootkatone) may enhance the protective effective bathing and showering practices by further discouraging tick attachment).

Residential prevention measures. Ticks can be encountered in many locations, including those visited for recreational activities. However, the majority of the more than 300,000+ human cases of Lyme disease acquired annually, particularly in the northeastern and eastern U.S. are thought to result from tick encounters mainly in the peridomestic (residential) landscape, thereby placing the responsibility for disease prevention mostly on individual householders to take either personal and/or household-level actions that reduce tick encounters and tick bites. Exposure to lone star tick and dog tick species across the U.S. can also frequently occur peridomestically, highlighting the need for affordable and effective residential tick control interventions. Residential tick control methods include targeted or broadcast applications of synthetic or botanically-derived acaricides, implementation of biological control agents, and deployment of rodent-targeted tick/pathogen control devices or baits. Additionally, landscape modifications that can discourage ticks and hosts can be implemented in a residential environment. Despite numerous published evaluations of residential tick control interventions, more proof-of-concept population-based studies validating residential tick control methods for the reduction of human-tick encounters and tick-borne diseases are needed.

Synthetic acaricides. Numerous small-scale field studies have demonstrated significant (up to 100%) tick reduction in individual backyards after a single treatment with an effective synthetic, tick-killing product, particularly pyrethroids (Curran, Fish, & Piesman, 1993; Schulze, Jordan, & Hung, 2000; Schulze et al., 2001; Schulze, Jordan, & Krivenko, 2005; Solberg et al., 1992; Stafford, 1991). Based on those studies, residential applications of synthetic chemical acaricides are a commonly recommended public health practice for preventing tick-borne diseases (Stafford, 2004; "TickEncounter Resource Center," 2018; Town of Ridgefield, 2018). But do residential application of effective tick-killing products alone represent the most effective practice for homeowners wanting to protect their families from ticks and disease? Unfortunately for the people who want to prevent tick-borne diseases, that question remains largely unresolved. For example, in a study of 2,727 households in three Lyme disease-endemic states, a single springtime application of an acaricide applied to individual yards in tick endemic communities resulted in an average of 63% fewer host-seeking nymph stage blacklegged ticks compared to untreated yards. In this study, however, the level of vector tick control failed to significantly reduce the number of human tick encounters recorded or cases of tick-borne disease (Hinckley et al., 2016). Reasons for a lack of disease reduction at properties are unclear but there are several possible explanations. It is possible that tick populations must be reduced below a particular (yet unknown) threshold, that reducing exposure risk in one targeted area of the backyard is not adequate to prevent disease (that is, that exposure to ticks may happen outside of the residential environment or in untreated regions of the backyard), and/or that other entomologic-, host-, and human-behavioral factors play a more critical role than we currently understand. It is also possible that the lower than expected reduction in tick abundance occurred due to variation in pest control operator (PCO) application methods, leading homeowners to take fewer backyard precautions. In this case, people believing they were well-protected by the spray, may have inadvertently increased their risk for exposure to ticks.

More studies validating chemical tick control as a means to reduce human tick-encounters and disease are therefore warranted, and may be enhanced by including measurements of human behaviors (both protective and risky) and peridomestic landscape features. Additionally, the development of educational materials for PCOs regarding best-practices for residential acaricide application may help applicators achieve the level of tick control that has been seen in published small-scale field studies.

Finally, although synthetic pyrethroids may offer the longest-lasting, effective backyard control of blacklegged ticks, it is important to note that misuse or poor application can result in harmful environmental effects (for example, toxicity to aquatic vertebrates) or deleterious health consequences (for example, toxic human exposures to pesticides or a false sense of safety). The degree to which well water and other waterbodies on residential properties are affected specifically as a results of pesticides applied for tick control (as opposed to those applied for lawn maintenance and tree care, for example) needs further study. In one survey of Connecticut wells, many herbicides and synthetic pesticides commonly used on lawns and trees were found to leach into groundwater; however permethrin pesticides were not detected (Addiss, Alderman, Brown, & Wargo, 1999). Permethrin readily binds to soil, is not water-soluble (and therefore does not leach well into groundwater,) and degrades slowly in the environment (USDA, 1990; Wagenet, 1985), suggesting that permethrin acaricides can offer long-lasting tick-killing effects, without major concern for groundwater pollution compared to other pesticides. Education about judicious and best practices for using acaricides as a means for tick control would benefit homeowners and pest management officials alike. Education for commercial PCOs about the most effective methods for applying pesticides for tick control is also warranted.

Botanically-based acaricides. Studies have ascertained botanically-based, all “natural” products for controlling ticks. Such natural products are appealing to the public because of perceived low toxicity to humans, pets, and the environment. Pyrethrin soaps, derived from chrysanthemum flowers, have limited residual control because they break down quickly with exposure to light and oxygen (Eisen & Dolan, 2016). Nootkatone from Alaskan yellow cedar and grapefruit essential oil also kills multiple tick species (Flor-Weiler, Behle, & Stafford III, 2011) but also breaks down rapidly, despite efforts to prevent volatilization using a lignin-encapsulation method (Bharadwaj, Stafford, & Behle, 2012). Many other natural products, such as those with rosemary oil or garlic oil active ingredients, have been field tested on ticks with some initial levels of control that were typically not long-lasting, 1-3 weeks post-treatment (Eisen & Dolan, 2016). In light of public interest in natural products for tick control, further work towards formulating botanically-based acaricides to make them more persistent in the environment is needed before such products can reliably be promoted as an effective means for controlling residential tick populations.

Biological control of ticks. Laboratory studies have identified several species of naturally-occurring soil-dwelling bacteria and fungi that are capable of killing several species of ticks (Kirkland, Westwood, & Keyhani, 2004). Field studies evaluating tick-killing *Metarhizium* fungi formulations have had varying but promising results for controlling host-seeking blacklegged ticks (Bharadwaj & Stafford III, 2010; Stafford & Allan, 2010). *Metarhizium* is of particular interest because of its low non-target effects (Ginsberg, Bargar, Hladik, & Lubelczyk, 2017). It should be noted that application timing and prerequisite environmental conditions needed for optimal tick control may be limiting factors to using entomopathogenic agents (Eisen & Dolan, 2016). Field studies have yet to confirm consistent results for biocontrol of ticks. Furthermore, no published studies have evaluated tick-killing biocontrol agents for reducing human-tick encounters or human tick-borne illnesses, and the high cost of treatment could limit the adoption of this treatment option by homeowners.

Rodent-targeted approaches for tick control Approaching tick control at the level of rodent reservoir hosts for tick-associated pathogens is meant to kill immature ticks on their host, interrupting the cycle of pathogen transmission between ticks and rodent reservoirs. One rodent targeted approach, Damminix Tick Tubes, seeks to kill ticks on rodents by providing permethrin-treated cotton for nesting material. Studies evaluating Damminix tubes have shown varied effects, ranging from a substantial reduction of ticks on mice in a residential setting in Massachusetts (Mather, Ribeiro, Moore, & Spielman, 1988), to little or no effect in the same region (Daniels, Fish, & Falco, 1991; Ginsberg, Butler, & Zhioua, 2002; Stafford III, 1991). It is possible that differences in small mammal diversity and abundance in the treatment areas greatly affect use of the tubes by possible reservoir hosts. Furthermore, the use of permethrin-treated cotton with a similar approach in the western U.S. did not control Western blacklegged ticks on dusky-footed woodrats (Leprince & Lane, 1996).

Another rodent-targeted intervention focuses upon the passive application of tick-killing fipronil onto mice and chipmunks as they visit the Tick Box™ Tick Control System (formerly Select TCS™ and MaxForce™ Tick Control systems). Field studies evaluating the boxes have provided consistently favorable outcomes. A residential field trial of bait boxes at closely-situated properties in a small Connecticut community resulted in both a significant reduction of ticks parasitizing mice as well as a reduction of infected host-seeking ticks in subsequent years (Dolan et al., 2004). A subsequent study showed that bait box use significantly reduced host-seeking blacklegged tick nymphs in the two years after boxes were deployed (Schulze, Jordan, Williams, & Dolan, 2017). Lastly, a recently study conducted in Connecticut sought not only to reduce entomologic risk factors, but also human-tick encounters and incidence of tick-borne diseases by conducting a randomized, placebo-controlled, blinded study of bait box use at 625 residences in Lyme-endemic communities. Results of this study have not yet been published, but will provide much needed data regarding the utility of using bait boxes not only for reducing ticks and tick infection rates, but as a means of disease reduction. The use of bait boxes is somewhat limited by their inability to treat a diversity of reservoir hosts including birds and insectivores and by their high cost to install ($50 per box, averaging 15 boxes per property = $800 per property) and maintain on an annual basis (Interlandi, 2018). Nonetheless, results of bait box field trials to date have yielded promising results. More study is needed to evaluate the utility of this measure for reducing human disease tick-encounters.

Rodent targeted transmission blocking vaccines. A reservoir-targeted *Borrelia burgdorferi* OspA oral vaccine reduced infection in the field in a Lyme endemic area in both white-footed mouse reservoir hosts and blacklegged ticks (Gomes-Solecki, 2014; Richer et al., 2014). Oral vaccination of white-footed mice with *Borrelia burgdorferi* OspA containing bait protected uninfected mice from infection and reduced transmission to ticks infesting mice infected prior to oral immunization (Voordouw et al., 2013). Reservoir targeted vaccine in the field over the five-year trial resulted in cumulative anti-OspA antibody production and significant reduction of tick infection over the course of the study (Richer et al., 2014). These studies support the use of a reservoir targeted vaccine as an effective tool to reduce Lyme spirochete infection in blacklegged tick nymphs, the primary vector of Lyme bacteria to humans. It should be noted, however, that rodent vaccination is limited to a single pathogen, and this methodology will not reduce tick abundance. Thus, another approach could be small mammal-targeted anti-tick vaccines (Bensaci, Bhattacharya, Clark, & Hu, 2012), which could reduce tick abundance as well as break enzootic cycles given their importance as reservoirs.

The effect of any reservoir-targeted intervention on reducing the density of infected nymphs depends on the relative contribution of mice (or other targeted rodent species) for feeding and infecting ticks. The relative importance of mice in turn may vary spatially and temporally depending on their abundance and that of other wildlife hosts comprising both reservoirs and incompetent hosts. Thus, replicate studies should be conducted to understand how the effect of host-targeted interventions vary in different ecological contexts. Furthermore, any intervention that acts as a selection factor on ticks or pathogens may select for resistance; research is therefore required to better understand the population biology of ticks and pathogens (for example, immigration/emigration rates) to predict the evolution of resistance under different selection scenarios and ecological contexts.

Landscape modifications. Health education efforts have long promoted the use of landscape modification tactics for preventing TBD. Specifically, homeowners are encouraged to create a “tick safe zone” where families can recreate with a low risk of exposure to vector ticks (Stafford, 2004). Such landscape approaches include measures like choosing ornamental plants that are unlikely to attract deer, keeping potential rodent breeding sites far from the home (for example. log piles), and recreating in the lawn far from forested edges where ticks are more likely to be abundant. There is some evidence that deer exclusion fencing can reduce backyard tick populations as well (Daniels, Fish, & Schwartz, 1993). Studies evaluating the use of landscape modification specifically for reducing human exposures to ticks are lacking. With a recent public interest in mulch-mowing (mowing lawns without leaf removal) for increased turf and pollinator health, there are questions about how such practices may affect backyard survival of some tick species. Nonetheless, landscape modifications may offer a pesticide-free option for reducing backyard risk for tick exposure, and warrant further study.

Community-level prevention

Deer removal. White-tailed deer play an important role providing blood meals for adult stage blacklegged ticks as well as lone star ticks. Experimental removal of deer in island settings of the northeastern U.S. have resulted in reductions of blacklegged tick populations (Rand, Lubelczyk, Holman, Lacombe, & Smith, 2004; Wilson, Telford, Piesman, & Spielman, 1988). On mainland settings, there are no studies evaluating experimental deer removal for tick population control, and the threshold of deer reduction required to control ticks is yet unclear. It also seems likely that even complete elimination of deer will not completely control tick populations, as adult ticks can find alternative hosts on which to feed (Fish & Dowler, 1989). Further studies are needed to better understand how deer removal can affect tick abundance and tick infection rates, particularly on mainland settings.

USDA 4-Poster devices. Several studies evaluating topical application of tick-killing pesticides on white-tailed deer using U.S. Dept. of Agriculture 4-poster deer feeding stations resulted in significant reductions in host-seeking lone star and blacklegged ticks several years after deployment (Brei et al., 2009; Carroll et al., 2003; Pound, Miller, George, & Lemeilleur, 2000). However, deployment of 4-poster devices is currently limited by municipal and state regulations, particularly as they apply to health concerns about feeding wildlife, increasing the transmission of pathogens in deer like chronic wasting disease and bovine tuberculosis, and human safety. The possibility exists to replace corn feed with a salt lick in these devices. Such a device had been patented by Kenneth Liegner, MD before the 4 Poster Device was available. It is yet unclear how feeding salt will affect how deer feeding stations impact tick populations, however. Furthermore, pesticide resistance as a result of widespread use of 4-poster is also a consideration for future use (Eisen & Dolan, 2016). Nonetheless, use of 4-poster devices offers an effective approach to broad scale tick control in tick-endemic areas.

Lizard removal. In the western US, experimental removal of western fence lizards that play an important role as hosts to immature western blacklegged ticks resulted in fewer Lyme bacteria-infected ticks in the region (Swei, Ostfeld, Lane, & Briggs, 2011). Although the lizards are not competent reservoirs hosts for Lyme bacteria, they do play an important role in the tick life cycle, providing further evidence that a broad-scale approach to host population control has potential to affect entomologic risk for Lyme disease.

Educational programs. Another integral component of community-based prevention is the implementation of public education programs for preventing tick bites, controlling tick populations, and recognizing symptoms of tick-borne illnesses. Educational needs and barriers are discussed in detail in Priority 5.

Integrated tick management. Only recently have tick-control efforts focused on application of multiple methods for controlling ticks in an integrated tick management (ITM) approach. ITM approaches can include targeting multiple life stages (for example, tick larvae parasitizing mice and host-seeking nymphal stage ticks), can result in reduced pesticide loads dispersed into the environment, and can be applied at different spatial scales (individual yards vs. neighborhoods, communities). ITM may also resulted in a slower development of pesticide-resistant ticks. A few studies have applied integrated methods for reducing tick populations, including combinations of perimeter sprays, bait boxes, and deer treatments, which have all resulted in a reduction of tick abundance, and in some cases, in a reduction of tick infection prevalence (Schulze et al., 2008; Schulze et al., 2007; Williams, Stafford, Molaei, & Linske, 2018). Given the promising approach of using ITM, there are currently three studies ascertaining the use of ITM for preventing blacklegged tick-associated diseases at single vs. clustered residential properties (www.backyardtickstudy.org), in neighborhoods (www.tickproject.org), and in communities (ARS Area-Wide Integrated Tick Management Study). Two of these three studies attempt not only to measure a reduction of entomologic risk factors, but also to ascertain whether an ITM approach can ultimately result in a reduction of human-tick encounters and in human disease incidence.

Novel tick control methods on the horizon

TickBot. A novel robotic device known as TickBot travels by following a guide wire, dragging permethrin-treated fabric behind it. It has been shown to reduce questing lone star ticks for 24 hours in the regions where it has been tested (Gaff et al., 2015), and is currently being evaluated for its effectiveness at controlling blacklegged ticks. TickBot has the potential to control ticks in backyards or along public trails, but may require multiple visits and maintenance to sustain tick control using this methodology. Further study of this new device is warranted.

Novel genetic approaches. The development of new genetic and molecular tools is allowing for novel generation of tick-borne disease prevention tools, including methodologies aimed at creating genetically modified organisms or disrupting gene expression in ticks and reservoir hosts.

The concept of releasing transgenic organisms (for example, animals that have modified genetic material, also known as genetically modified organisms or GMOs) has long been discussed and tested for controlling populations of vector mosquitoes and crop pests, and may also offer great promise for effective vector control in regions where ticks are hyper-abundant. Transgenic ticks are currently in development at the University of Nevada-Reno, with a goal of using a new genetic tool known as CRISPR to disrupt insulin signaling, which plays a role in nutrient metabolism and therefore parasite survival in ticks (Feinberg, 2018). CRISPR technology is also being explored by researchers at the Massachusetts Institute of Technology for genetically engineering white-footed mice to become reservoir-incompetent for Lyme bacteria and other tick-borne pathogens (Harmon, 2016). The use of GMOs may offer great possibility for eradicating blacklegged ticks in hyper-abundant areas, in contrast to just control as achieved by using other technologies.

RNA interference (RNAi) is one powerful reverse genetic approach used to determine gene function and to silence tick genes (Fire et al., 1998). The use of RNA interference in ticks continues to increase from 30 early studies using this tick gene silencing technology to assess interactions at the tick-pathogen interface (de la Fuente & Contreras, 2015). A far more extensive reporting of RNA interference studies in ticks is that of Galay et al (Galay et al., 2016). RNAi works well to silence genes within tick tissues. These studies of ticks encompassed the topics of pathogen acquisition/transmission, protective antigens, structural and metabolic proteins, reproduction, digestion, and roles of salivary gland proteins (Galay et al., 2016). This technology can be used to assess potential targets for acaricides, repellents, anti-tick vaccines, and other strategies to disrupt tick physiological processes, and tick-borne pathogen interactions within the tick vector and at the host interface. It can potentially be used to disrupt virus infection within the tick (Hajdusek et al., 2013).

RNAi applied experimentally to silence tick genes is labor intensive, and slow to yield results (Lew-Tabor et al., 2011; Tuckow & Temeyer, 2015). Broad application of an RNA interference-based approach to tick and tick-borne disease control would require significant technological advances in delivery and targeting systems, as well as consideration of any off-target impacts. Practical wide scale application technologies and developing ways of prolonging the mode of action of RNA interference in the tick need to be investigated because this tool has great potential to help us discover molecules essential for controlling ticks and their ability to transmit disease-causing microbes.

Other emerging technologies. There are several potential technologies for tick/pathogen control and tick bite prevention that may have promise for reducing the incidence of human tick-borne diseases in the U.S. and warrant additional study to validate their effectiveness. Such technologies include the aforementioned nootkatone repellent and tick killing products and salt lick-baited deer feeding stations, emerging genetic tools and robotic tick control devices. Other possible technologies and methodologies that have not yet been extensively-evaluated for tick-borne disease prevention include drone-assisted area-wide tick management, controlled burning as a means of tick management, and encouraging populations of natural enemies and predators of ticks and their hosts. In addition, the relationship between plant dynamics and entomologic risk for tick-borne diseases could also be further elucidated (such as in the case of oak acorn masting in the northeastern U.S., and Sudden Oak Death in the western U.S.). Finally using semiochemicals as a means to arrest and kill vector ticks is a methodology that warrants further study. For example, one product in development, Splat TKTM, utilizes a novel attract-and-kill approach to minimize the amount of acaricide by combining it with a pheromone specific to blacklegged ticks. The pheromone causes the ticks to remain in contact with the acaricide, causing a lethal dose to be delivered. Technology such as Splat TKTM that use semiochemicals synergistically with existing vector control methods may offer options for mitigating concerns about toxicity (to the environment, animals, and humans), as well as pesticide resistance.

Also see:

https://pubag.nal.usda.gov/pubag/downloadPDF.xhtml?id=62302&content=PDF

Stafford III, K. C., S. C. Williams, and G. Molaei. 2017.Integrated pest management in controlling ticks and tick-associated diseases. Journal of Integrated Pest Management 8: 28.https://doi.org/10.1093/jipm/pmx018

Conclusions and Recommendations:

The challenge of managing the multitude of factors that contribute to the occurrence and severity of tick-borne disease outbreaks is far more complex than can be addressed in a single document, or by a single agency or land manager for that matter. When invasive species are introduced to the already complex natural cycle of tick-borne diseases, their vectors, their various host species, and ultimately their victims, it is impossible to effectively consider the issue as a single topic. The only way to effectively approach management actions that can mitigate the risk of tick-borne diseases is to determine which part of the complex consideration of risk mitigation land management activities will target, and which part of the often complex life cycle of the vectors, the diseases, their hosts or habitat can be manipulated to produce results that actually work, and do so a cost-effective and environmentally acceptable impact.

For federal land managers, one step in the process of determining priority management strategies is to determine the most important management goals for a parcel of federal property, or who the most important constituents and uses of that property may be. Then, it is more feasible to identify and assess the greatest risks to those constituents and activities may be from tick-borne diseases. Once the most likely or dangerous disease risk is identified, the role of invasive species management in the overall response to that disease risk can be studied.

For example, at U.S. military installations and training facilities, clearly the presence and welfare of uniformed personnel, contractors, and military families is a higher priority than the health of the general public, since access to the facilities is often limited and specific activities more predictable and consistent. For managers of the National Parks, the priority will typically be the members of the general public who visit the parks, and for Park Service personnel who live and work within park boundaries. For National Wildlife Refuges, the health and welfare of native wildlife, potentially including threatened or endangered species, is likely to be a priority, along with the protection of refuges staff, hunters, and other recreational users. On National Forest Lands and Bureau of Land Management lands, in addition to the wildlife, resources, and recreational users, many regions allow the grazing of livestock that is privately owned, complicating the issues of resource management, and the consideration of tick-borne disease that may pass back and forth between domestic animals, wildlife, and people.

It is generally acknowledged that the incidence of tick-borne disease is on the increase in many parts of the United States, especially within specific regions. While Lyme disease is only one of a plethora of tick-borne diseases being tracked and studied across the United States, it is the most frequently reported tick-borne disease in the U.S.. Lyme's Disease is spreading rapidly across the twelve states of Northeast, Mid-Atlantic, and North Central regions (where 95% of the cases are currently found) and is expected to soon emerge as a major threat in new regions. Lyme's disease provides a very useful case study for the broader study of tick-borne diseases because it has been very thoroughly studied, and vividly illustrates the complexity of the life-cycle of the tick vectors spreading this disease, and the challenges of trying to manage or control the outbreak. Consequently, Lyme's Disease has been used in this document as the primary example of tick-borne pathogens, to illustrate the disease cycle, the role that Ixodid ticks play at various lifestages in the acquisition and spread of the disease, and the role that intermediate host speices (primarily white-footed mice and white-tailed deer) play providing a reservoir for the disease, and assistance for the ticks to complete their life-cycles.

In the process of compiling this document, it was found that multiple federal agencies and programs are focused on one aspect or another of tick-borne diseases, many with robust studies underway. While many of the scientists and researchers within the agencies are acquainted with one another on a professional basis, it quickly became clear that there is no central clearinghouse within the federal government, or even an effective communication network through which the primary stakeholders can readily access current and comprehensive information about various tick-borne disease issues on either a topical or regional basis. This already flawed situation is worsened when the role of invasive species (plants, tick, hosts, and pathogens) is added to the mix. While a National Invasive Species Council exists as a result of Presidential Order XX the principles within each of the member agencies have not met for eleven years to discuss how sharing information and resources related to invasive species could advance the agencies' primary missions, whether that be the protection of human health, agriculture, natural resources, or national security and defense. As a result, federal land managers do not have a single source for information about which invasive species may exist on their respective land units, what role—if any—those invasive species have in the risk of tick-borne disease, or what control or eradication measure can be considered for invasive species that could mitigate the risk of tick-borne disease on a given land unit or regional division of an agency charged with any form of land management activities.

There are various agency experts monitoring tick populations in certain regions, but not in others. Some researchers monitor ticks for their role in human disease, while others monitor for the disease implication in livestock and domestic animals. Even though these studies may be looking at the same ticks, this information does not exist in a single database, in spite of the fact that the majority of tick-borne diseases are zoonotic; that is, able to be spread back and forth between humans and animals. There is little comprehensive study being given to the issue of tick-borne diseases affecting wildlife, beyond the role that various wildlife species play in the life-cycle of ticks, or the transmission and spread of various diseases.

Unfortunately, for federal land managers, this will make the job of making land management decisions that can mitigate the risk of tick-borne diseases more complex and daunting. Nevertheless, taking the time to identify and tap into regional expertise, databases, and disease studies, could help tremendously, especially when there is a targeted constituency, land use mission or activity on which land management activities are focused, or regionally emergent diseases that may be present on, or approaching, a given land management unit.

As a result of these studies and findings, the Invasive Species Advisory Committee makes the following recommendations to the National Invasive Species Council for ways assist the federal government, across all agencies to mitigate the risk of tick-borne diseases which are amplified or exacerbated or complicated through the presence of invasive species.

Recommendation 1 – Within NISC member agencies and bureaus, assure that scope of Invasive Species Programs and activities embraces the One Health Concept and is sufficiently broad to facilitate an integrated response to issues related to role of invasive species in human health, animal health, and/or environmental health. It is important to break the mindset that invasive species management is carried out on a species-by-species basis, often in a policy vacuum; rather, the issue of invasive species must be viewed in the context of broader management activities and goals, with assurance that the impact of controlling or eradicating invasive species be evaluated in the context of full ecosystem health. Where necessary, formal communication and information sharing networks within a single agency need to be created and mandated to assure that information sharing is carried out in a timely manner to facilitate cooperation among programs responsible for human safety and health, facilities and land management, and the specific management of invasive species (which could have implication for the first two).

Recommendation 2 – NISC agencies with active programs related to the mitigation of risk associated with tick-borne diseases that affect humans or animals, most notably HHS/CDC and USDA, should create and fund a formal information-sharing network or task force that gathers and compiles available information related to invasive diseases, plants, vectors or pathogens of interest to more than to each respective agency, and proactively share this information with all NISC agencies, targeting human and animal health professionals and environmental and landscape managers. The purpose of this task force, and that for which they should be held accountable, would be to create more comprehensive data resources on which other agencies of the federal government, or state and local entities, can predicate land or resource management decisions that could affect the risk of tick-borne diseases on either a region or local basis. Communication can be in the form of a regular electronic digest or a website that assembles the points of access to all relevant federal information related to resource management studies, recommendations, or activities which could be of use to federal personnel and all federal partners or collaborators.

Recommendation 3 – Land and facility managers of all NISC agencies should identify and establish communication with regional experts and personnel within CDC, USDA, (or other agencies) who may have relevant information relevant to land management decisions they need to make related to the issue of tick-borne disease. This can be prioritized within the context of the respective land manager's mandate or land management priority, whether human heath, animal health, environmental health, or other land-use mission. This communication should be such that it facilitates a regular and timely flow of information, recommendations, expertise, or advice on how best to identify and implement regionally relevant invasive species management and related disease risk mitigation strategies. For example, in certain parts of the country, invasive species of plant, such as Japanese Honeysuckle and Japanese Bayberry are known to create artificially lush habitat for high risk disease vector ticks, while also providing abundant vegetation for deer and other host species that exacerbate the spread of disease. In other parts of the country, tick-borne disease risk may be minimal. Understanding which invasive species have the greatest impact on the density of vectors or the likelihood of questing ticks to come in contact with wild or domestic host species, could enable managers to prioritize invasive species management activities, especially when resources and personnel are limited.

Appendices and references

8 – Wildlife factors affecting occurrence and density of ticks

Large increases in white-tailed deer populations in the 20th century may have facilitated the expansion of ticks and Lyme disease (Léger et al. 2013). High deer densities are common in many parts of the Midwest and mid-Atlantic regions due to extirpation of predators, decreased hunting pressure, and human-driven habitat fragmentation leading to more edge areas with high-quality forage (Côte et al. 2004). Deer are also the primary host for adult-stage I. scapularis ticks and thus are a key blood meal for egg mass production; several studies have reported a positive relationship between deer density and tick density (Raizman et al. 2013, Kilpatrick et al. 2014, Werden et al. 2014, Kugeler et al. 2015). As selective herbivores, deer have indirect effects on ticks by altering tick habitat (Fisichelli et al. 2013) and other tick hosts (e.g., small mammals and songbirds, Habeck and Schultz 2015), but few studies have evaluated how these effects may influence pathogen systems. Intense deer browse pressure, due in part to overabundant populations, can alter and fragment understory vegetation structure and plant community composition (Mudrak et al. 2009, Fisichelli et al. 2012), causing simplified forest understories with abundant non-native and unpalatable plant species and dramatic reductions in understory-dependent mammal and bird species (Rooney et al. 2004, Fisichelli and Miller GET CITATION). Dominance by less-palatable or browse-tolerant non-native and invasive shrubs is positively related to I. scapularis and pathogen abundance (Lubelczyk et al. 2004, Elias et al. 2006, Williams and Ward 2010).

Based on the observed differences in host competence for B. burgdorferi infection, previous models have suggested that biodiversity, i.e., a diverse animal community including non-competent hosts, can 'dilute' B. burgdorferi infections in a system (Ostfeld and Keesing 2000). Additionally, host superinfection, and transmission competence to feeding ticks, is dependent upon B. burgdorferi diversity within the host (here Peromyscus leucopus), which is dependent upon the number of ticks feeding on the host (Rogovskyy and Bankhead 2014). This suggests that hosts feeding more ticks are also more effective at transmitting B. burgdorferi to feeding ticks. Supporting this hypothesis, larger, older, male mice are more likely to be infected with B. burgdorferi and also carry higher tick loads regardless of questing tick aggregation in the environment (Ostfeld et al. 1996; Brunner and Ostfeld 2008; Devevey and Brisson 2012). Additionally, the proportion of adult, larger, male mice is inversely related to forest patch size and consequently bird and mammalian diversity (Nupp and Swihart 1996). In this way, forest patch size, which is driven largely by human-driven landscape change, may drive host infection prevalence and thus tick infection prevalence. Predation is also linked to tick-borne disease risk, which predator richness and density linked to lower risk of Lyme disease, and is also inversely related to forest patch size (Hofmeester et al 2017).

Hofmeester, T. R., Jansen, P. A., Wijnen, H. J., Coipan, E. C., Fonville, M., Prins, H. H. T., Sprong, H., and S. E. van Wieren., 2017. Cascading effects of predator activity on tick-borne disease risk. Proc. R. Soc. B. 284: 20170453.

9 – Habitat factors affecting occurrence and density of ticks

For many tick-borne diseases, a certain number of host relationships and seasonal dynamics of ticks are required to maintain a robust enzootic cycle. There must be established relationships between environmental conditions and tick-host associations, as both vertebrate host populations and tick questing behavior are influenced by abiotic factors (distributional limits, abundance, and seasonal dynamics) (Sonenshine and Clifford, 1973). A tick's geographical distribution, life history, hosts, and its ability to transmit diseases are determined by biochemical and physiological aspects of the tick that determine its reaction to temperature, humidity and other meteorological elements (e.g., the number of offspring produced per reproductive cycle)/ In addition to climatic factors, the spatial structure of the landscape and its connectivity and vegetation types also have an effect on tick populations and their distributions (Estrada-Pena et al., 2008).

Ticks are intermittent parasites, spending part of their lives off their hosts in habitats where they are influenced by abiotic factors. Temperature and rainfall are the main factors affecting the ecology and population dynamics of tick species, and these operate at critical levels on selection of tick populations (Estrada-Pena et al., 2009). For example, the distribution of Ixodes ricinus in Britain was associated with several environmental factors, such as substrata composed of less permeable soil types and less permeable superficial/bedrock geology, which would support moist microhabitats. Their distribution was also associated with calcareous/neutral grassland and heathland habitats, particularly those grazed by livestock (Medlock et al., 2008). McEnroe (1977) reported that there were relative differences in the distribution of the American dog tick from region to region, likely due to moisture and temperature differences. Campbell (1979) reported shifts in tick distribution and abundance related to vegetative types and attributed environmental determinants to tick survival.

Tick abundance is also limited by abiotic factors that influence the ability to actively quest for a host. Questing ticks are influenced by a variety of abiotic factors such as increasing or decreasing day length or fluctuations in temperature. Additionally, temperatures can change the questing behavior in ticks; for example, decreasing temperature associated with increasing altitude will negatively affect the number of questing numbers of nymphs and adults (Randolph, 2004). Therefore, the opportunity to acquire a pathogen from a reservoir host can be positively or negatively impacted by abiotic factors. It has been observed with I. ricinus nymphs that drier conditions impacted the questing height, with more nymphal ticks questing lower and thus having increased exposure to rodents. In contrast, in wetter conditions, an increased number of larvae attached to rodents and fewer nymphs. These climatic factors influenced the questing behavior and thus the potential for a pathogen to be transmitted by nymphs or larvae feeding on rodents. The risk of infection to hosts depends on the number of infected questing ticks. In addition, the larger the number of hosts in an area the greater the probability of ticks attaching and progressing through their life cycle and transmitting a pathogen (Kitron and Kazmieerczak, 1997; Randolph, 2001).

Ecological information on tick species within in the United States is vital for developing and implementing a systematic approach to tick control. The assessment of the developmental times of the free-living tick stages on vegetation will be helpful in determining the major tick species' seasonal activities. With the additional analysis of environmental temperature, rainfall, and tick abundance, this information will aid in the prediction of peak abundance of ticks and the timing of appropriate tick control on a seasonal basis.

Through the integration of field, laboratory, and modeling studies, we can gather new insights into the mechanisms of evolutionary ecology regarding the diverse spectrum of tickborne pathogens, tick species, and their vertebrate hosts.

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10 – Climate change and landscape affecting occurrence and density of ticks

It is important to consider any management challenge in light of additional stress to the system. Both vector borne disease and invasive species challenges are likely to be further complicated by climate dynamics: especially continued warming trends, extended droughts, and extreme events. Climate change can contribute to the spread of mosquitoes and ticks. A warmer climate enhances the suitability of habitats that were formerly too cold to support mosquito and tick populations, thus allowing these vectors, and the diseases they transmit, to invade new areas (NCA 4, figure X.1). Climate change is aiding the spread of invasive species (Burgiel and Hall, 2014). Climate projections show that habitat for certain species will increase (e.g. Berberis thunbergii [Japanese barberry] in the Northeast, see figure X.2 from Merow et al 2017). Climate change can favor nonnative invading species over native ones (Sorte et al, 2013, Wolkovich and Cleland 2014,). Extreme weather events can influence the invasion process, from initial introduction through establishment and spread, and potentially put native species at a competitive disadvantage (Diez et al 2012). Because vector borne diseases and invasive species are compounded by climate change, a holistic approach to managing invasive species and ticks (and other vectors) could help a) avoid surprises as either (or both) become worse and b) ensure proper resources are in place to manage landscapes that are resilient to climate dynamics.

Figure X.1 (from the 4th National Climate Assessment)

Figure X.2 (from Merow et al. 2017 NOTE: if used permission would be needed):

Current and future (2041-2050) predicted habitat suitablity for B. thunbergii, white dots show the locations of known current occurences.

References:

Burgiel and Hall, 2014. Bioinvasions in a Changing World: A Resource on Invasive Species-Climate Change Interactions for Conservation and Natural Resource Management. 10.13140/2.1.4868.6889.

Diez et al. 2012. Will extreme climatic events facilitate biological invasions?. Frontiers in Ecology and the Environment, 10(5), pp.249-257.

Sorte et al, 2013. Poised to prosper? A cross-system comparison of climate change effects on native and non-native species performance. Ecology Letters, 16 (2), 261-270. http://dx.doi.org/10.1111/ele.12017.

Merow, Bois, Allen, Xie, and Silander, 2017. Climate change both facilitates and inhibits invasive plant ranges in New England. Proceedings of the National Academy of Sciences, 114(16), pp.E3276-E3284.

Wolkovich and Cleland, 2014. Phenological niches and the future of invaded ecosystems with climate change. AoB PLANTS, 6, plu013-plu013. http://dx.doi.org/10.1093/aobpla/plu013.

Background.

From the 4th National Climate Assessment

From the NCA 4 Frequently Asked Questions:

Does climate change increase the spread of mosquitoes or ticks?

Yes. Climate change can contribute to the spread of mosquitoes and ticks. A warmer climate enhances the suitability of habitats that were formerly too cold to support mosquito and tick populations, thus allowing these vectors, and the diseases they transmit, to invade new areas.

Background for point #1::

From NCA 4:

“Impacts from climate change on extreme weather and climate-related events, air quality, and the transmission of disease through insects and pests, food, and water increasingly threaten the health and well-being of the American people, particularly populations that are already vulnerable.” p. 27.

In particular: Vector-Borne Diseases

“Climate change is expected to alter the geographic range, seasonal distribution, and abundance of disease vectors, exposing more people in North America to ticks that carry Lyme disease or other bacterial and viral agents, and to mosquitoes that transmit West Nile, chikungunya, dengue, and Zika viruses.(30,31,32) Changing weather patterns interact with other factors, including how pathogens adapt and change, changing ecosystems and land use, demographics, human behavior, and the status of public health infrastructure and management.(33,34)” p. 545

The following is from

USGCRP, 2016. The Impacts of Climate Change on Human Health in the United States: A Scientific. Assessment. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp. http://dx.doi.org/10.7930/J0R49NQX

“The seasonality, distribution, and prevalence of vector-borne diseases are influenced significantly by climate factors, primarily high and low temperature extremes and precipitation patterns. Climate change is likely to have both short- and long-term effects on vector-borne disease transmission and infection patterns, affecting both seasonal risk and broad geographic changes in disease occurrence over decades (see Figure ES6). While climate variability and climate change both alter the transmission of vector-borne diseases, they will likely interact with many other factors, including how pathogens adapt and change, the availability of hosts, changing ecosystems and land use, demographics, human behavior, and adaptive capacity. These complex interactions make it difficult to predict the effects of climate change on vector-borne diseases."

Invasive species: Climate change is aiding the spread of invasive species (nonnative organisms whose introduction to a particular ecosystem causes or is likely to cause economic or environmental harm). Invasive species have been recognized as a major driver of biodiversity loss.61,62,63 The worldwide movement of goods and services over the last 200 years has resulted in an increasing rate of introduction of nonnative species globally,64,65 with no sign of slowing.66 Global ecological and economic costs associated with damages caused by nonnative species and their control are substantial (more than $1.4 trillion annually).61 The introduction of invasive species, along with climate-driven range shifts, is creating new species interactions and novel ecological communities, or combinations of species with no historical analog.67,68 Climate change can favor nonnative invading species over native ones.69,70 Extreme weather events aid species invasions by decreasing native communities' resistance to their establishment and by occasionally putting native species at a competitive disadvantage, although these relationships are complex and warrant further study.71,72,73,74 Climate change can also facilitate species invasions through physiological impacts, such as by increasing per capita reproduction and growth rates.69,75,76" p.276-277.

"Warmer winters will likely contribute to earlier insect emergence74 and expansion in the geographic range and population size of important tree pests such as the hemlock woolly adelgid, emerald ash borer, and southern pine beetle.75,76,77 Increases in less desired herbivore populations are also likely, with white-tailed deer and nutria (exotic South American rodents) already being a major concern in different parts of the region.78" p. 679.

11 - Invasive pathogens considered tick-borne diseases (Clinical signs, diagnostic tools)

https://www.cdc.gov/ticks/longhorned-tick/index.html; https://www.cdc.gov/mmwr/volumes/67/wr/mm6747a3.htm

Tick-borne FAD	Natural/Potential U.S. Vectors	Geographic Distributions	Commodity

1. Equine piroplasmosis	*Dermacentor variabilis; Dermacentor albipictus;* *Anocentor nitens;* *Amblyomma mixtum;* *Boophilus microplus*	Multiple States Texas	Equine
2. Bovine babesiosis	*Rhipicephalus Boophilus microplus;* *Rhipicephalus Boophilus annulatus*	Texas only, both species	Cattle
3. African swine fever	*Ornithodoros coriaceus;* *O. turicata; O. parkeri*	Multiple States	Swine
4. Heartwater - Cowdriosis	*Amblyomma maculatum;* *A.mixtum; A. dissimile*	Southern states	Cattle

1. Heartwater
https://avmajournals.avma.org/doi/pdf/10.2460/javma.237.5.520

2. Equine piroplasmosis
https://www.aphis.usda.gov/animal_health/animal_diseases/piroplasmosis/downloads/ep_literature_review_september_2010.pdf

3. Bovine Babesiosis
https://pdfs.semanticscholar.org/7340/4c91761c117207e5ad205a5a5546ddb06286.pdf

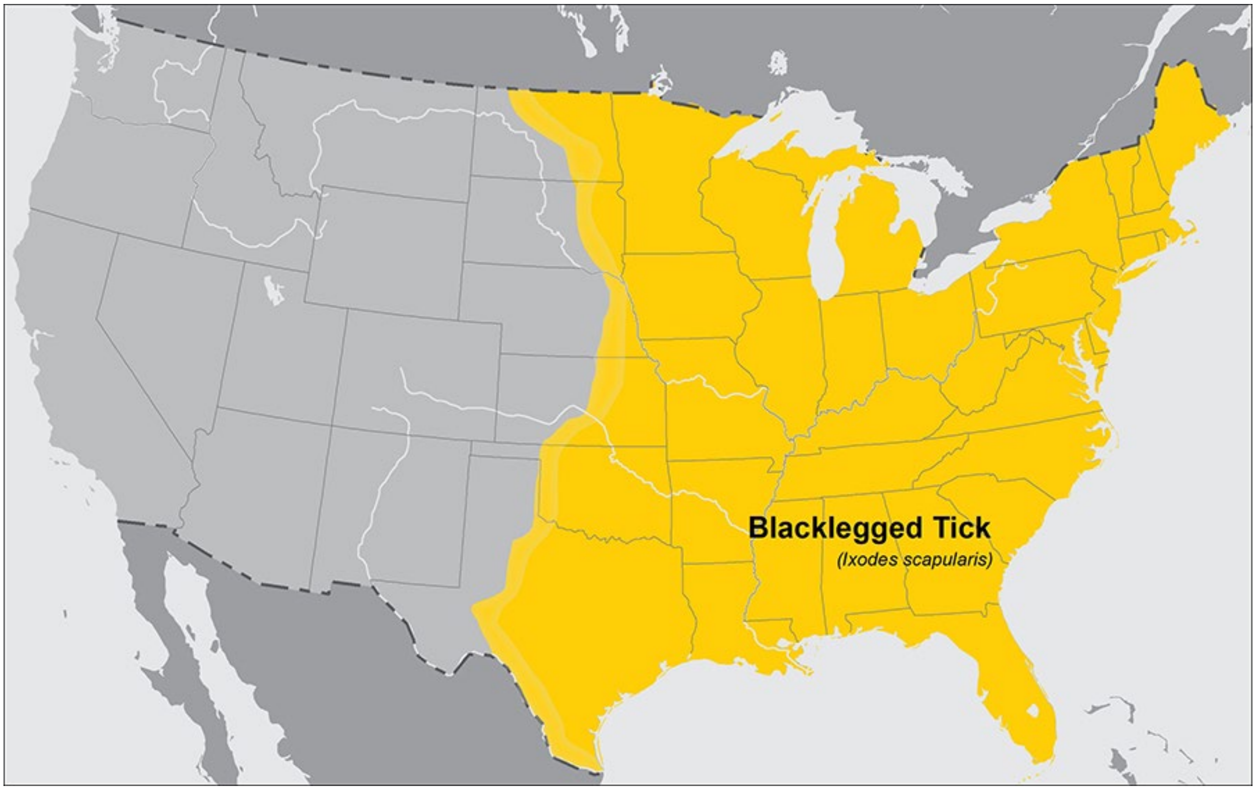
4. African Swine Fever
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5808196/pdf/fvets-05-00011.pdf

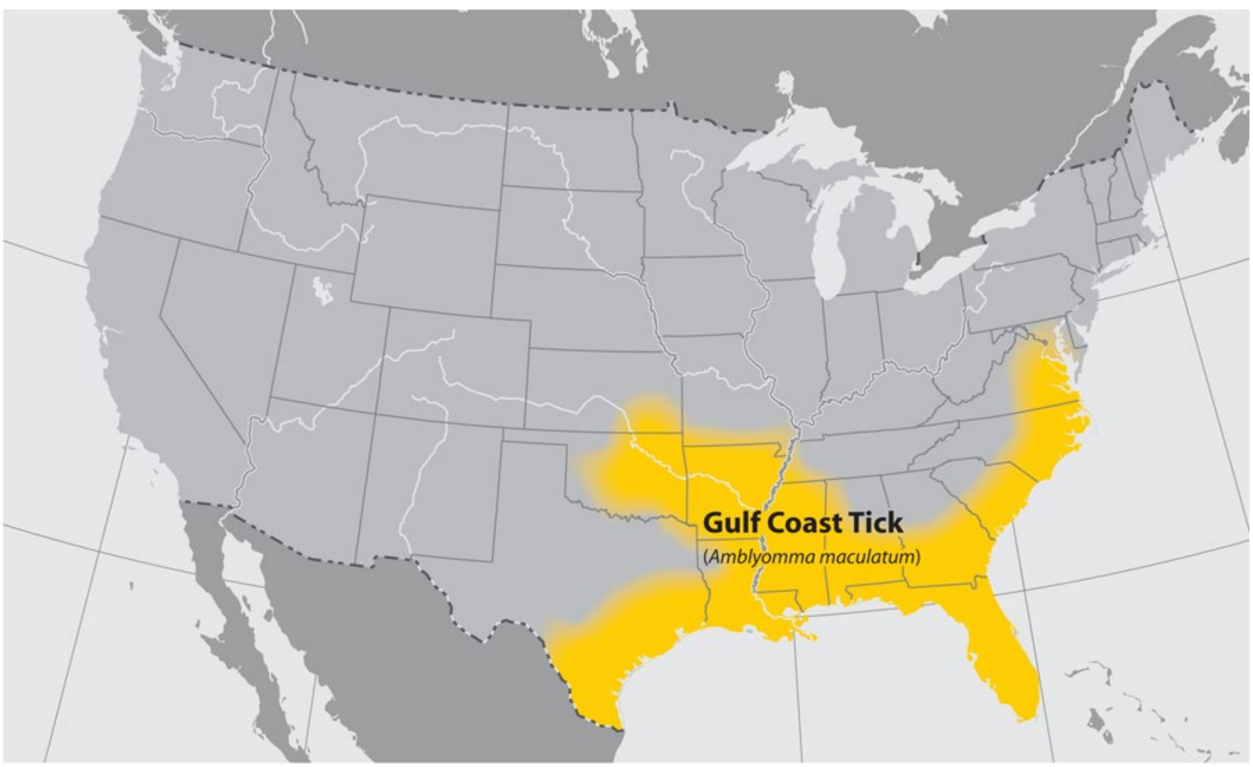
12 – Updated Maps of Medically Important Tick Distribution

Updated maps of tick distribution

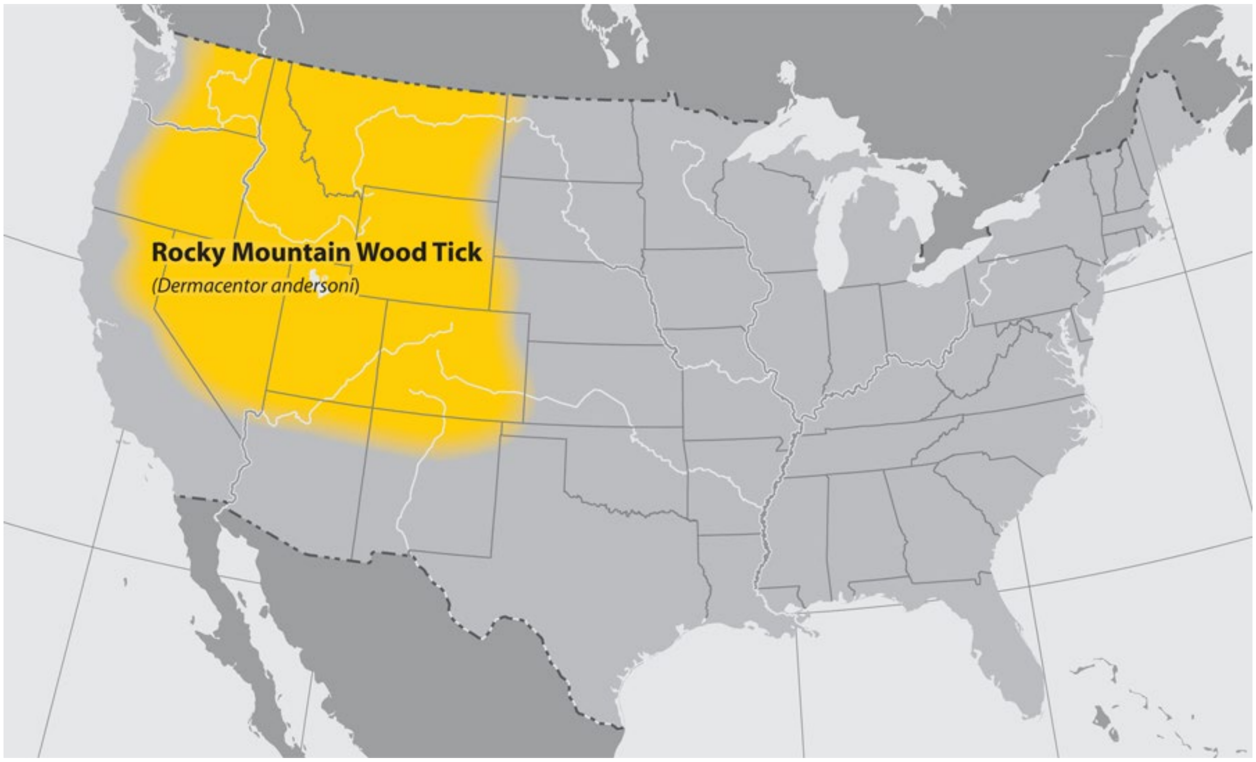
Distribution of Tick-borne diseases found here: https://www.cdc.gov/ticks/tickbornediseases/overview.html

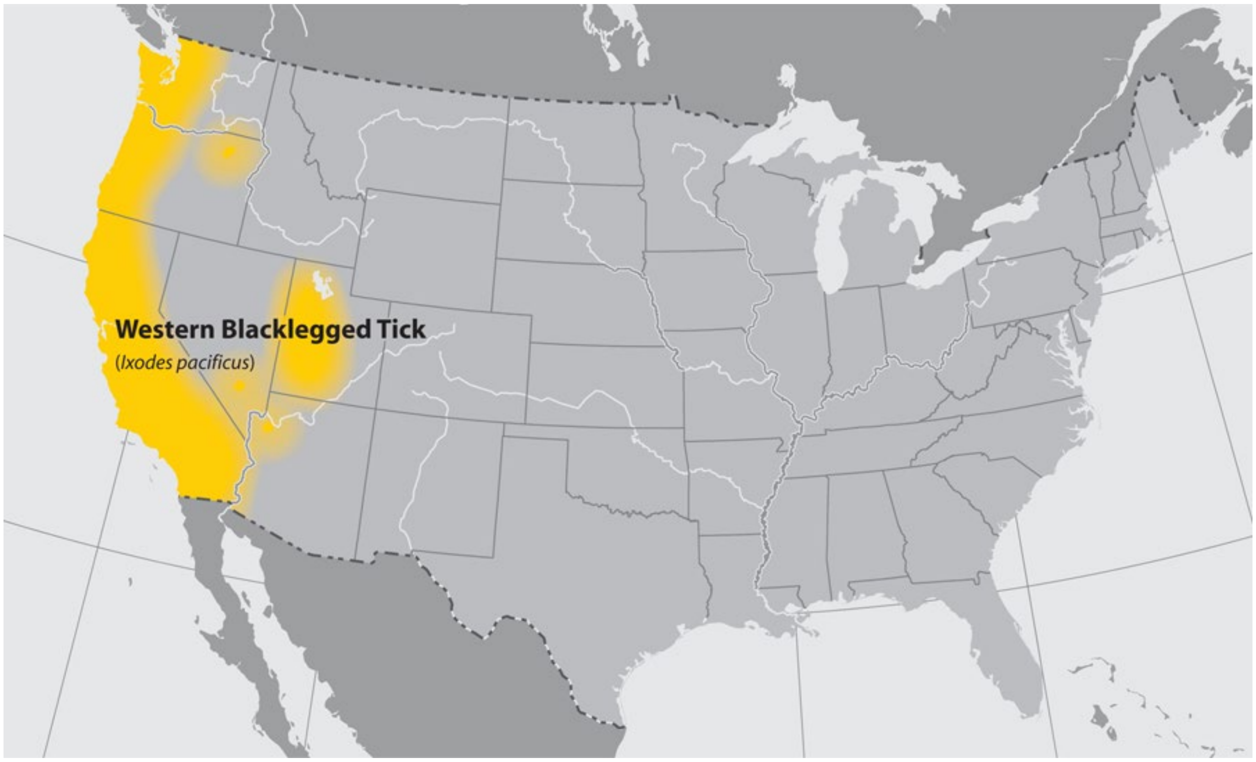
Distribution of medically important tick species distributions. See: https://www.cdc.gov/ticks/geographic_distribution.html


Blacklegged Tick
(Ixodes scapularis)


Gulf Coast Tick
(Amblyomma maculatum)


Lone Star Tick
(Amblyomma americanum)


Rocky Mountain Wood Tick
(Dermacentor andersoni)



Distribution of Tick-borne diseases found here: https://www.cdc.gov/ticks/tickbornediseases/overview.html

Also check maps in these publications:

Int J Environ Res Public Health. 2018 Mar 9;15(3). pii: E478. doi: 10.3390/ijerph15030478.

Sci Rep. 2019 Jan 24;9(1):498. doi: 10.1038/s41598-018-37205-2.

13 - Data types for monitoring ticks and tick-borne diseases (links, names, resources)

Data types for monitoring ticks and tick borne diseases (links, names, resources)

Check here for details of excerpts below: https://www.hhs.gov/ash/advisory-committees/tickbornedisease/reports/disease-vectors-2018-5-9/index.html

Major challenges – surveillance. Currently seven tick-borne diseases are nationally notifiable in the U.S. In 2016, Lyme disease was the most common vector-borne disease reported and the sixth most common of all nationally notifiable diseases. While approximately 35,000 cases of Lyme disease are reported each year to the CDC, recent studies indicate that the actual number of annual cases exceeds 300,000 (Hinckley et al., 2014; Nelson et al., 2015). Under-reporting is a common phenomenon for most high-incident diseases, and Lyme disease under-reporting is further complicated by a case definition that requires both laboratory and supportive clinical data for confirmation of all but the earliest manifestations of the illness. National disease reporting, while coordinated by CDC, is formally a responsibility of state governments through the Council of State and Territorial Epidemiologists (CSTE). CSTE determines, through votes of its membership, which diseases are nationally-notifiable and the specifics of case definitions. The resulting data are submitted to CDC where the information from each state is collated and made available nationally. Accurate and up-to-date incidence data for all tick-borne diseases, including Lyme disease, are critical in order to demonstrate the burden of illness in terms of both economic cost and human suffering, to establish baselines against which to measure prevention efforts and to monitor disease emergence in new geographic areas. Under-reporting and inconsistencies in surveillance data from state to state and from year to year significantly hamper efforts to raise public awareness of the magnitude of the problem and provide data needed to evaluate prevention effectiveness.

Topic 3: Drivers of vector range expansion and vector/disease ecology

There is a broad consensus among scientific experts that ticks have been expanding their geographic ranges since at least the middle of the 20th century (Clow et al., 2017; Eisen et al., 2016; Hahn et al., 2016; Medlock et al., 2013; Sonenshine, 2018). The drivers of vector tick range expansion are numerous and complex, but two major factors stand out and likely explain most of the reasons for this phenomenon, namely, climate change (especially global warming) and bird migrations. Though differing viewpoints on climate change have been recently published from a Canadian researcher which in addition to migratory birds, implicates that growing public awareness is driving factor for observed changes in tick distribution (Scott & Scott, 2018). Anthropogenic changes in the landscape, increasing populations of suitable host species and suitable tick habitat (Mixson, Lydy, Dasch, & Real, 2006; Ogden et al., 2006; Ogden, St-Onge, et al., 2008) also have contributed to tick range expansions. Similarly, changing populations of predators have been proposed to have effect on major tick host populations (Levi, Kilpatrick, Mangel, & Wilmers, 2012; O'Bryan et al., 2018). The evidence for these changing conditions and their implications for human and animal health are discussed below. A better understanding of the geographic distribution of the tick vectors, disease ecology and vectorial capacity, and how these factors are changing over time will help identify the key entomological determinants of risks to humans, including tick behavior and vector competence

Evidence and Findings

Arthropod vectors of pathogens are expanding their ranges because of climate change and shifting patterns of land use, resulting in dramatic and often unpredictable effects on human and wildlife health (Kilpatrick & Randolph, 2012). In North America, climate change, especially major warming trends, have expanded northward across the continent. The result is that most of the north-central and northeastern U.S. and even extensive areas of the mid-western region now have average above freezing temperatures during the winter months. Maps from the National Oceanic and Atmospheric Administration (NOAA) show that the -10-200 F. average temperature for January, which covered most of the north central and northeastern U.S. in 1970, now covers the region from northern Michigan, Wisconsin, Minnesota, North Dakota and northern Montana in the mid-west and small, isolated areas in northern New York and New England. Ticks can survive over the winter if soil temperatures hover near or slightly below freezing. Blacklegged ticks (*Ixodes scapularis*) have compounds in their body fluids (hemolymph) that function like a type of anti-freeze, enabling them to survive sub-zero temperatures (Neelakanta, Sultana, Fish, Anderson, & Fikrig, 2010). Furthermore, as with other ticks and insects, given that the rates of many physiological processes are temperature-dependent, warmer temperatures (up to a point) for a longer portion of the year can improve tick survivorship rates due to increased probabilities of host-finding and developing to the next life stage (or ovipositing eggs) before the onset of colder winter temperatures (Lindsay et al., 1998; Ogden et al., 2005). Recent research findings conducted in Canada found that lack of snow cover negatively affects the survival rate of overwintering adult ticks (Scott & Scott, 2018).

Maps of tick geographic distributions were published in 1945 (Bishop & Trembley, 1945). These maps show the ranges for 4 of the most important tick vectors in the U.S. All were located in the southern or mid-central regions of the country, and none were in Canada. Since that time, the geographic range of the American dog tick, *Dermacentor variabilis,* now covers almost all the eastern United States as well as in isolated foci in southern Canada. The blacklegged ticks, *I. scapularis*, the vector of the Lyme disease agent, *Borrelia burgdorferi*, has expanded northward into northern New York, all of New England, and even into parts of southeastern Canada. This phenomenon is mostly related to the re-introduction and proliferation of white-tailed deer (*Odocoileus virginianus*), which were almost exterminated in the previous century, as well as bird migration (Scott & Scott, 2018). Similarly, lone star ticks, *Amblyomma americanum*, the major vector of human monocytotropic ehrlichiosis (HME), have spread northward and now covers most of the eastern U.S. as well as large areas of the mid-central United States (Monzon et al., 2016). An even more remarkable range expansion is that of the Gulf Coast Tick, *Amblyomma maculatum*, a major pest of cattle and other livestock as well as a vector of *Rickettsia parkeri*, the causative agent of a spotted fever-like illness. This species, formerly limited only to the south Atlantic and Gulf coast region of the U.S., has now spread northward along the Atlantic coast as far as Delaware, as well as in the mid-west to Oklahoma and Kansas and in parts of southern Arizona. Similar examples of tick range expansion have occurred in Europe and northern Asia, particularly for the sheep tick (*Ixodes ricinus*) and the taiga tick (*Ixodes persculatus*), vectors of the Lyme disease agent in those regions (Medlock et al., 2013).

Studies suggest the following as main driving forces of the drastic changes in the geographic ranges of these tick vectors.

- **Warming winter temperatures**. Climate change has been forecasted to increase tick habitat in the coming years. Studies have shown that the rising temperatures in the winter can increase the survival of ticks in winter, is already facilitating tick range expansions worldwide, and is increasing the risks of tick-borne diseases (Cumming & Van Vuuren, 2006; George, 2008; Leger, Vourc'h, Vial, Chevillon, & McCoy, 2013). Maps of weather patterns accumulated during recent decades have shown the warming patterns, especially in winter months (December through March) (see Figure 2 for January mean temperature changes). However, research recently completed in Canada over a 5-year period presents a differing viewpoint on influence of climate change on tick spread and prevalence. In their studies, these workers found that when there was consistent snow cover, 90% of the adult ticks survived the winter but fewer survived when temperatures were warmer with little snow cover (Scott & Scott, 2018). This study identifies migratory birds and increased public awareness as the drivers for tick distribution changes.
- **Migratory birds**. Of the four major North American vectors of tick-borne disease noted above, *I. scapularis, A. americanum* and *A. maculatum* readily feed on birds, especially ground-feeding birds. Ground feeding birds that become infested with immature ticks drop engorged larvae and nymphs when they stop periodically to feed during their flights to their artic nesting grounds. Following the early reports by Morshed et al. (Morshed et al., 1999) and Scott et al. (Scott et al., 2001), more recent studies have shown that tens of millions of larval and nymphal ticks, primarily *I. scapularis*, are deposited in numerous locations in the northern U.S. and Canada((Ogden, Lindsay, et al., 2008) during the spring migration period, often establishing new tick foci and spreading tick-borne pathogens (Loss, Noden, Hamer, & Hamer, 2016).
- **Changing vertebrate host populations**. Ticks depend on the movements of their hosts to facilitate dispersal across the landscape, and are particularly vulnerable to environmental pressures, such as desiccation, when they live away from their hosts (Leger et al., 2013). The increasing and expanding white-tailed deer populations in the U.S. and Canada will provide optimal hosts wherever the ticks range (Paddock & Yabsley, 2007). Furthermore, changes in landscape and land use (see below) that influence the dispersal of deer and other tick hosts will also affect the spread of ticks. Accidental transport by humans, livestock, and companion animals contributes to these events, as does ticks carried by illegal trade in exotic species.
- **Anthropogenic factors**. Land use by humans have resulted in an increased abundance and diversity of arthropod disease vectors, including mosquitoes (Norris, 2004) and ticks (Brownstein et al., 2003; Childs & Paddock, 2003). Lyme disease is the best-known tick-

borne disease associated with landscape changes, as reforestation, along with white-tailed deer management, may have resulted in an increase in Lyme disease risk (Barbour & Fish, 1993). Also, forest fragmentation and loss of biodiversity have been proposed to increase human disease risk (Allan, Keesing, & Ostfeld, 2003; LoGiudice, Ostfeld, Schmidt, & Keesing, 2003; Ostfeld & Keesing, 2000) but there have been few studies actually demonstrating causal relationships (Diuk-Wasser et al., 2012; Linske, Williams, Stafford, & Ortega, 2018; Ogden & Tsao, 2009; Randolph & Dobson, 2012; Salkeld, Padgett, & Jones, 2013; Wood & Lafferty, 2013; Zolnik, Falco, Kolokotronis, & Daniels, 2015). Studies have shown that the removal of weedy species and restoration of habitat can reduce Lyme disease risk (Gilbert, 2013; Morlando, Schmidt, & LoGiudice, 2012), and the removal of invasive plant species can result in a reduction in lone star ticks and effectively reduce disease risk (Allan et al., 2010).

- **Invasion by exotic species**. Accidental transport by humans has resulted in numerous instances of exotic ticks being relocated to new geographic regions where they may become established. Examples include the transport of Gulf Coast ticks on cattle to new locations in the southcentral and mid-western U.S., the accidental introduction of the Japanese tick (*Haemaphysalis longicornis* to a sheep paddock in New Jersey (Rainey, Occi, Robbins, & Egizi, 2018) and the import of African ticks to Florida by illegal trade of snakes and other reptiles.

Tick distributions may also shrink and go extinct (locally). An example is the decrease in detection of *I. muris*, which used to be more abundant in New England, but then declined as *I. scapularis* became more abundant (Spielman, Levine, & Wilson, 1984).

Priority 3: The Need for Improvements in National Human Tick-borne Disease Surveillance and Reporting, and the Potential Role of Other Data Sources and Patient Registries in Defining National Disease Burdens and Trends

Public health surveillance is the ongoing, systematic collection, analysis, interpretation, and dissemination of data regarding a health-related event for use in public health action to reduce morbidity and mortality and to improve health (German et al., 2001). The 10th Amendment to the U.S. Constitution states that “The powers not delegated to the United States by the Constitution, nor prohibited by it to the States, are reserved to the States respectively, or to the people ("Tenth Amendment: Reserved Powers,").” Given that “public health” is not mentioned explicitly in the Constitution, the primary authorities and responsibilities for public health actions, including public health surveillance, belong to state governments.

Public health surveillance is useful to appreciate whether a disease is common or rare, to gain a general understanding of who is affected by the disease, and to monitor how the disease changes over time. Traditional public health surveillance is a passive process whereby healthcare providers and laboratories report positive diagnoses or laboratory tests to public health agencies; passive surveillance is known to have limitations, regardless of the disease under surveillance. It is unrealistic to expect that every case of disease under public health surveillance will be ascertained, especially when the disease is common. As with Lyme disease, when there are lag times for diagnostic testing, reporting and investigation, there is often significant delay from the time a patient becomes ill to when the disease is reported to public health agencies. Hence, it is also not possible to expect real time reporting of diseases as they occur or even as they are diagnosed clinically.

Notifiable diseases are those for which regular, frequent, and timely information regarding individual cases is necessary for disease prevention or control. Diseases are deemed nationally notifiable and surveillance case definitions are developed by the Council of State and Territorial Epidemiologists (CSTE). The intent of developing a surveillance case definition is to ensure that cases are counted the same way by all jurisdictions for public health purposes; surveillance case definitions include clinical, diagnostic and epidemiologic criteria that must be met in order for a case to be counted. Surveillance case definitions can have inherent limitations, such as when there are vague clinical manifestations (such as nonspecific signs and symptoms) and/or if there are limitations in the available diagnostic tests. Surveillance case definitions are **not** developed to guide clinical diagnosis or management, nor should they be used for those purposes.

When a disease is first considered for surveillance, or if changes are necessary to an existing case definition, a proposal for a surveillance case definition is drafted and presented to the CSTE membership by active CSTE members, typically state health department surveillance personnel familiar with and responsible for that particular disease. Proposed case definitions are discussed and modified, and ultimately voted on with one vote per state or U.S. territory. Currently, Lyme disease, babesiosis, anaplasmosis, ehrlichiosis, tularemia, and spotted fever rickettsioses are nationally notifiable tick-borne diseases ("CSTE List of Nationally Notifiable Conditions," 2013).

Given that public health surveillance is a state responsibility, it is important to note that the determination for whether a disease is reportable in a given state or territory lies with that jurisdiction, regardless of whether the disease is deemed nationally notifiable. A disease might be nationally notifiable, but not reportable in a state, as illustrated by Lyme disease which is nationally notifiable but not reportable in Hawaii (Health, 2013). This might happen if the disease does not occur naturally in that jurisdiction or there are other diseases considered of greater public health importance by that jurisdiction. States generally designate which diseases are reportable in state law or regulation, although how diseases are deemed reportable varies across jurisdictions.

Public health surveillance is conducted locally; cases of disease are reported to the local or state health department by healthcare providers, diagnostic laboratories and whoever else is required by law to report in that state. Reports are investigated by public health surveillance personnel and a determination is made as to whether the case conforms to the surveillance case definition and should be counted. If the case is counted at the local or state level and is nationally notifiable, the case is reported to the federal Centers for Disease Control and Prevention (CDC). The CDC analyzes the data to describe the patients affected by the disease (for example, young vs. old) and where the disease occurs (that is, does it occur regionally or is it distributed across the whole of the U.S.). Cases counts for notifiable diseases are published regularly (weekly or annually, depending on the disease) in the Morbidity and Mortality Weekly Report (CDC, 2017b) and summaries describing the surveillance findings are published as updated surveillance data accumulate (Schwartz, Hinckley, Mead, Hook, & Kugeler, 2017).

As the number of cases of tick-borne disease (Lyme disease in particular) has increased over time, the burden on the public health system for investigation has also increased. Further, given that no immediate community intervention is implemented when most tick-borne disease cases are detected, such as might be done for diseases with other transmission mechanisms such as foodborne or by direct contact , many public health jurisdictions have lowered the priority of conducting tick-borne disease (specifically Lyme disease) surveillance (Rutz, Hogan, Hook, Hinckley, & Feldman, 2018). Because disease surveillance (specifically Lyme disease surveillance) is conducted specific to each jurisdiction's resources and perceived needs, surveillance practices can be variable across jurisdictions and underreporting of cases is common. Recent estimates, as determined through systematic analyses, of the actual number of cases of Lyme disease in the United States range from eight to ten times the number of cases than captured through traditional public health surveillance (Hinckley et al., 2014; Nelson et al., 2015). This section addresses three issues surrounding public health surveillance of tick-borne diseases, specifically:

- How can surveillance practices be improved and standardized from state-to-state and from year-to-year?
- What is the role of other data sources and patient registries in defining national disease trends?
- Would the Council of State and Territorial Epidemiologists (CSTE) consider other surveillance data than case numbers?

Evidence and Findings

The committee identified improvements in national human tick-borne disease surveillance and reporting, and the potential role of other data sources and patient registries in defining national disease burdens and trends as a priority. Understanding the true burden of disease in a population and knowing who the disease affects are essential for the allocation of resources and for targeting public health interventions.

Public health surveillance is a "passive" process, whereby healthcare providers and laboratories report positive diagnoses and/or laboratory tests to public health agencies. On receipt of a positive report, public health personnel conduct investigations to collect additional information and classify the cases according to standard case definitions. Passive surveillance systems work best for diseases that are rare, involve hospitalized patients, or for which there are definitive diagnostic laboratory tests. Passive systems work less well for common diseases that are typically diagnosed in outpatient settings and for which there are no definitive laboratory tests (Cartter, Lynfield, Feldman, Hook, & Hinckley, 2018). Lyme disease, the most commonly reported vector-borne disease in the United States, falls into the latter category, and underreporting of Lyme disease is well documented and generally acknowledged (Cartter et al., 2018; Rutz, Wee, & Feldman, 2018; Schiffman et al., 2018; White et al., 2018).

There are many contributing reasons as to why Lyme disease is underreported, including the complexity of the national case definition and testing criteria (Cartter et al., 2018; CDC, 2017a; Rutz, Wee, et al., 2018; Schiffman et al., 2018; White et al., 2018). Other reasons include the effort required for healthcare providers to report and the burden on public health practitioners to conduct public health investigations for surveillance purposes. Substantial underreporting can obscure trends and may inhibit the ability to evaluate the effectiveness of interventions. Underreporting can also lead to a lack of awareness on the part of the public and the healthcare community that tick-borne diseases are a risk in a particular geographic area. This lack of awareness of Lyme and other tick-borne diseases prevents practitioners from considering them when generating differential diagnoses. The most extreme consequence of this is the possibility for disease to go unrecognized and therefore untreated, with potentially fatal consequences

(Box 1) Fatal Lyme Carditis Case Study. Seventeen-year-old Joseph Elone, an honor student at Poughkeepsie (NY) High School, died suddenly in August, 2013, after having been sick for about a month with flu-like symptoms. Early in his illness, the young man tested negative for Lyme disease – however, this test was administered too early to provide serologically relevant results. The patient was also dark skinned, and no *erythema migrans* rash was visible. Joseph had recently returned from a 2-week exposure to tick habitat during the peak of Lyme disease season, but was not prescribed antibiotics. After he died, health officials initially suspected tick-borne Powassan virus; that has since been ruled out and it was determined that Joseph in fact had disseminated Lyme disease. An autopsy showed Lyme spirochetes in his liver, heart, lungs and brain. The official cause of death was Lyme carditis—a condition which interferes with electrical signals in the heart. It is possible that the surveillance case definition was used to rule out this less common presentation of Lyme disease, based on the negative serologic test. Had antibiotics been prescribed, this young man's life might have been saved.

(Box 1, (Yoon et al., 2015).

To add complexity to the concerns regarding underreporting, tick-borne disease reporting and public health investigations vary from state to state, further complicating the ability to make comparisons, monitor trends and detect emergence of the disease. It is therefore important that all states report Lyme and other tick-borne diseases similarly.

A review of the literature regarding public health surveillance for Lyme disease documented underreporting and provided estimates of the actual number of cases of Lyme disease (that is, the true burden of illness) that are eight to ten times the number captured by public health surveillance (Figure 3). A recent survey assessed tick-borne disease laboratory testing practices at large commercial laboratories, and the data were used to estimate the number of infections among patients from whom specimens were submitted. The authors estimated 240,000-444,000 infected source patients in 2008 (Hinckley et al., 2014). Another recent retrospective analysis used data from a nationwide health insurance claims database. That analysis yielded comparable results to the earlier study: the estimated Lyme disease incidence is approximately ten times that reported through public health surveillance (estimated 329,000 (95% credible interval 296,000–376,000) Lyme disease cases annually as compared to approximately 36,000 cases reported in 2013 through public health surveillance) (Nelson et al., 2015).

Other studies have assessed alternative approaches to Lyme disease surveillance. In New York State, a system was developed to estimate county-level Lyme disease cases based on a 20% sample of positive Lyme disease laboratory reports, thereby reducing the burden on the public health system to conduct public health investigations. The system was determined to be accurate and efficient in estimating the true number of cases and the demographic and clinical characteristics as captured by public health surveillance (Lukacik, White, Noonan-Toly, DiDonato, & Backenson, 2018). Similarly, 20% and 50% retrospective samples of Lyme disease reports in Massachusetts and Minnesota, respectively, generated estimated counts of Lyme disease that were similar to observed counts as captured through traditional public health surveillance. Moreover, demographic and clinical characteristics of cases as ascertained through sampling were not significantly different from those captured through traditional public health surveillance (Bjork, Brown, Friedlander, Schiffman, & Neitzel, 2018).

Other alternative surveillance approaches have assessed the use of administrative datasets to complement or replace public health surveillance. These approaches relied on using diagnostic codes, assigned for a patient's medical encounter for the purposes of charging for services, to identify cases of Lyme disease. There were varying degrees of success (Clayton, Jones, Dunn, Schaffner, & Jones, 2015; Robinson, 2014; Rutz, Hogan, et al., 2018) across these approaches, and there might be other viable approaches that have yet to be explored. Underlying these approaches, however, is the reliance on standard codes that are typically part of an electronic health record and transmitted electronically. A recent assessment of medical practices that see Lyme disease patients demonstrated that most practices were able to electronically search records using specific diagnostic and billing codes, suggesting that automated, electronic reporting of cases to public health agencies is possible and could ease the reporting burden on providers (Thomas et al., 2018).

Finally, disease registries might serve as another complementary source of data to understand the number of individuals affected, characterize those affected and examine the risk factors for disease. Registries are likely more useful for rare diseases or rare manifestations of disease (for example, Lyme carditis), and would require strict criteria for inclusion. One possible model to consider for the development of a tick-borne disease registry is the congressionally mandated national registry for amyotrophic lateral sclerosis (ALS, also known as Lou Gehrig's disease). The National ALS Registry uses administrative and self-reported data to identify cases instead of relying on provider or laboratory reports, as does traditional public health surveillance (Mehta et al., 2018).

Opportunities

The evidence we reviewed allowed us to identify potential opportunities for improving surveillance of tick-borne diseases. Chief among the opportunities is using multiple approaches to build a more robust understanding of the actual number of cases and risk of disease. "Burden of illness" studies estimate the actual number of cases by using alternative datasets and analytic methods; the results of these "burden of illness" studies can be used to complement traditional public health surveillance and present a more complete picture of the impact of the disease in a community, region, or entire country. CDC could report on its website and in written publications (for example, the Morbidity and Mortality Weekly Report) reported case counts from traditional public health surveillance in addition to estimates of the actual number of cases of disease based on "burden of illness" studies such as those conducted by Hinckley and Nelson. If adequate resources were allocated to conduct "burden of illness" studies on a regular, periodic basis (that is, annually) using consistent methodology, these estimates could be used to assess trends over time. These efforts to present a more complete picture of the impact of tick-borne disease will be for naught, however, if they are not accepted by the authoritative public health agencies, included in formal reports of disease incidence, and considered when making decisions about resource allocation.

Alternative surveillance approaches could also be used to ease the burden of tick-borne disease surveillance while providing valuable insights into disease incidence. Efforts could include systematic sampling of tick-borne disease reports for subsequent public health investigation (for example., a 20% sample of all reports are investigated, as implemented in New York State) or laboratory-only reporting. Disease registries, maintained by the public health community, healthcare systems, healthcare providers, patient advocacy groups or others, may also serve as a source of data on disease incidence. Disease registries might be particularly useful for determining the burden of illness due to rare tick-borne diseases or less common manifestations of tick-borne disease, such as Lyme carditis. Alternative approaches should include validation of these methods and the development of procedures (for example, generation of multiplication factors) to estimate true burden from these alternative approaches. Public health authorities, such as the CSTE and CDC, should accept alternative approaches to traditional public health surveillance as accepted mechanisms for characterizing how much disease occurs.

Alternative datasets (for instance tick surveillance data) can be used to build a more robust picture of risk. Data to consider for addition (and some may be of limited availability): tick surveillance data, tick testing data, companion animal tick-borne disease testing data; medical claims data; weather data; other patient data sources; data from other federal agencies including the Department of Defense. These data are frequently collected and published in white papers and in the peer-reviewed literature and provide valuable context for human case data and enhance our understanding of changing tick-borne disease risks. Considerations for this action include a) the need to determine how to integrate these datasets for a more complete picture of disease risk; b) the need to package and communicate the risks for consumption by the general public. By overlaying datasets, powerful visuals are unlocked than can tell more informative stories about risk than human surveillance data alone. For examples, see Figure 4 and the interactive map of Lyme disease risks in California (available at https://www.arcgis.com/apps/SocialMedia/index.html?appid=91d8639cf4d74b2db6cf36415f4bc9a1)

Finally, leveraging the growing use of electronic health records and the electronic exchange of health data (for example, through Health Information Exchanges) to automate, and thereby simplify, disease reporting is an opportunity to improve tick-borne disease surveillance. The education of healthcare providers could potentially improve tick-borne disease surveillance. Education could include which tick-borne diseases are notifiable, diagnostic test interpretation, and the obligation to report to public health agencies. The opportunity to educate healthcare providers could also be used to reinforce that the surveillance case definition comprises a set of criteria for how to count cases by public health agencies, and should not be used for diagnostic or clinical management purposes. Healthcare providers could be incentivized to report by ensuring that deliverables (such as annual updates from the CDC or CSTE with updated risk maps, recent range expansions, or updated diagnostic information) are made available to providers in a timely fashion. An interactive online risk index based on the location of where the tick bite was acquired would also take reported information and provide a useful tool to providers identifying tick-borne disease in their communities.

Threats or Challenges

Most tick-borne disease investigations at local health departments are triggered on receipt of a positive laboratory test. Currently, the high volume of cases of tick-borne disease, in particular Lyme disease, is such that public health investigations are limited and at times not conducted at all. However, the sheer volume of cases is not the only reason accounting for underreporting. When there are competing public health priorities for which immediate interventions can be taken, tick-borne disease investigations will often fall in priority.

Lyme disease is most typically diagnosed in outpatient settings, and understanding and interpreting the diagnostic laboratory tests is challenging even for medical professionals. Thus, patients might not be diagnosed appropriately (false positive diagnoses and false negative diagnoses might occur) or a provider may fail to recognize a situation that warrants testing or reporting, especially when a patient resides in a locality that does not appear to be at risk for Lyme disease based on reported surveillance case counts. Moreover, early Lyme disease (for instance patients with an *erythema migrans* rash) can (and should) be diagnosed clinically (also considering other factors such as tick exposure, tick habitat exposure, seasonality of the disease, and travel history) and not rely on diagnostic tests which are often negative early in the course of disease, as the immune system is still mounting its response. Thus, reporting of clinically diagnosed cases relies entirely on the healthcare provider, a notoriously weak link in the surveillance continuum, as there will not be a laboratory result sent to the health department.

There is also likely underreporting of rarer or lesser-known tick-borne diseases (that is, ehrlichiosis, some rickettsioses, tickborne relapsing fever) that may present with nonspecific signs (for example, “summer flu”) and might not ever get diagnosed. Because underreporting results in fewer numbers of cases reported in official surveillance summaries and reports, when *erythema migrans* rashes (or other Lyme disease clinical manifestations) occur outside of identified endemic states, they are often dismissed because providers do not believe that Lyme disease is present in these areas. The lack of awareness of the risks of tick-borne diseases by both the public and the healthcare community can have potentially fatal consequences.

Resources for monitoring ticks and tick-borne diseases:

- Army Public Health Center: Army Vector-Borne Disease Report https://phc.amedd.army.mil/news/Pages/PeriodicPublications.aspx
- Tick Trapper App: https://ticktracker.com/
- The Tick App / University of Wisconsin: https://thetickapp.org/
- Tick Insiders / Purdue University: https://tickinsiders.org/tick-encounter-disease-risk-map/
- CDC / Tick-Borne Diseases Home Page: https://www.cdc.gov/ticks/
- The Tick App for Texas and the Southern Region / Texas A &M University: https://tickapp.tamu.edu/
- USGS Disease Maps: https://diseasemaps.usgs.gov/

14 – Monitoring Techniques for tick-borne diseases in humans

https://www.cdc.gov/ticks/surveillance/index.html

15 – Monitoring techniques for tick-borne diseases in domestic animals

Effective surveillance for the detection of tick-borne diseases is essential to their control. As the livestock and poultry populations grow and with increased trade worldwide, there is an increasing likelihood of tick-borne disease outbreaks. Tick-borne diseases continue to have economic impacts on world health and many tick-borne pathogens are expanding their range into new areas. For example, an outbreak of African swine fever in West Africa resulted in the loss of approximately 50% of the pig population and in Malaysia an outbreak of Nipah virus resulted in a 45% loss of that country's swine (Martin et al., 2007). Tick-borne diseases pose substantial threats to livestock especially in view of the climate changes that are occurring globally.

Tick surveillance is used to determine changes in the geographic distribution and abundance of a tick species changes in vector populations in time and space, and provide appropriate recommendations regarding intervention strategies. It can also aid in the identification of areas with increased populations over short and long term periods and detect a new species appearing in an area. A number of methods are available for the detection and monitoring tick populations. The selection of the appropriate sampling method depends on the surveillance objective, the tick species of concern, current levels or abundance of the vector populations, and availability of resources.

Sampling Methods

Routine sampling of tick populations is critical in understanding the estimated levels of both infected and uninfected ticks. Ticks are typically collected, sent to an appropriate laboratory alive, or preserved in ethanol, and assayed for identification and infection. The methods of collection (e.g. dragging the ground with a flannel cloth or trapping) will vary with the tick species as well as the handling and packaging methods and according to the pathogen involved. For surveillance purposes, ticks are trapped, identified, sorted by sex, age, physiological type etc., counted and stored for later assays (Armed Forces Pest Management Board, 1998).

Tick sampling data in surveillance involves an estimation of tick density or abundance. Tick density in a region is important to understand because high tick densities have been shown to be associated with (high risk) outbreaks of certain tick-borne diseases. It should be noted that ticks are often introduced into an area without actually being infected with a pathogen. Tick presence in an area alone can pose a risk to livestock and humans (e.g. Heart water vectors in the US and Caribbean). Many sampling tools are available and the choice of that tool depends on the tick species and the surveillance question.

Many hard ticks "quest for a host" on vegetation, they are collected by dragging a large square piece of cloth (1 square meter) over the ground. If the vegetation is too thick, then a square cloth can be made into a flag that can be waved across the vegetation. In addition, for ticks that "hunt" for their hosts, CO2 traps are placed on the ground to attract ticks to a "sticky" surface where they can be collected or they are trapped within a recipient. Ticks can also be collected from hosts, but this method may select for tick species that remain on the host for long periods of time or certain stages such as adult males, and this method is further complicated by the movement of the host; all of these factors make sampling design key in determining relative abundance in an area (Armed Forces Pest Management Board, 1998).

Globalization and climate changes influence vector-borne disease epidemiology and these changes can influence both vector and pathogen distributions, how pathogens are transmitted, and interactions between vectors and host (Tabachnick, 2009). The challenges today are the development of vector surveillance systems that continue to collect epidemiological information on vectors, storage of that data, processing of the data, and analyses that will allow for monitoring of current changes in vector populations and prediction of future populations changes with our changing global environment. Climate-related environmental factors can be used as predictive indicators for vector habitat suitability studies and these studies can used to target vector surveillance activities. Satellite measurements and remote sensing techniques cannot identify the vectors themselves, but they can identify and characterize suitable vector habitats. Remote sensing techniques can aid in the development of distribution maps and disease risk on a seasonal basis and monitor changes in distributions and disease risk over time. Maps showing seasonal risks of vector-borne diseases will be critical in monitoring the impacts of global climate changes on vectors. Remote sensing can be used to determine the influence of environmental factors on the spread of vectors or possible increases in distributional boundaries. Remote sensing and other geospatial technologies are integral to any vector surveillance program and remains an important tool in predictive veterinary epidemiology (Martin et al., 2007).

Diagnostics

Veterinary Services has a national diagnostic laboratory that provides some data on certain livestock and equine diseases. The majority of the vector-borne disease diagnostic tests are assessing foreign animal diseases in the United States such as equine piroplasmosis. Veterinary Services is reliant on state laboratories, universities, other federal agencies, and local research institutions for endemic vector-borne disease prevalence datasets. For example, VS CEAH staff conducted a survey of NAHLN laboratories to determine their available laboratory tick-borne diseases diagnostic services and if they were collecting any tick distribution data. The state laboratories that responded to our survey indicated that a large number of tick-borne disease diagnostic services were available. They offered diagnostic services for six species of the genus Anaplasma, three species of the genus Babesia, three species of the genus Borrelia, four species of the genus Ehrlichia, one species of the genus Francisella, one species of genus Rickettsia, and one species of the genus Theileria {USDA, 2014 #67}.

Webpage: National Veterinary Services Laboratories
https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/lab-info-services

Webpage: National Animal Health Laboratory Network:
https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/sa_lab_information_services/sa_nahln/ct_national_animal_health_laboratory_network

16 - Monitoring techniques of tick-borne diseases in wildlife (List diagnostics, apps, webpages, etc)

Proc Biol Sci. 2017 Sep 13;284(1862). pii: 20170475. doi: 10.1098/rspb.2017.0475.

Ticks Tick Borne Dis. 2019 Feb;10(2):365-370. doi: 10.1016/j.ttbdis.2018.11.018. Epub 2018 Nov 27.

Vector Borne Zoonotic Dis. 2011 Apr;11(4):439-42. doi: 10.1089/vbz.2009.0221. Epub 2010 Sep 16.

Comp Immunol Microbiol Infect Dis. 2019 Apr;63:58-65. doi: 10.1016/j.cimid.2018.12.007. Epub 2019 Jan 9.

One Health. 2019 Feb 11;7:100083. doi: 10.1016/j.onehlt.2019.100083. eCollection 2019 Jun.

17 – Mitigation strategies of tick-borne diseases in humans (graphs and simple actions) for citizens, health professionals, and military personal

https://www.cdc.gov/ticks/tickbornediseases/tick-bites-prevention.html; https://www.cdc.gov/lyme/prev/in_the_yard.html; https://portal.ct.gov/-/media/CAES/DOCUMENTS/Publications/Bulletins/b1010pdf.pdf?la=en

From: Armed Forces Pest Management Board Technical Guide No. 26 Tick-Borne Diseases: Vector Surveillance and Control. 2012.
https://www.acq.osd.mil/eie/afpmb/docs/techguides/tg26.pdf

From Doug Burkett - Note, material from our TG 26 is slightly dated.

Tick Control

a. Integrated Control

Tick control measures should be tailored to the biology and seasonality of particular tick species. Additional considerations include the type of habitat involved, density and activity of the human population, incidence of infection in the vector species, extent to which tick control is necessary, and degree of environmental modification that is permissible. Based on a knowledge of when infected stages are most active, a medical or installation authority may recommend complete avoidance of some areas at certain times. Integrated tick control comprises four functions: personal protection (see above), habitat modification, acaricide application, and deer exclusion (Fig. 1).

b. Habitat Modification

Where acceptable, clearing of edge habitats by leaf litter removal, mechanical brush control, and mowing or burning vegetation are effective means of tick control in residential areas, bivouac sites, and certain recreational areas. Removal of low-growing vegetation and brush eliminates the structural support that ticks need to contact hosts, thereby reducing the incidence of tick attachment. Removing leaf litter and underbrush also eliminates tick habitats and reduces the density of small mammal hosts, like deer mice and meadow voles. Without leaf litter, ticks are denied suitable microhabitats that provide the necessary environmental conditions for survival, such as high relative humidity. Mowing lawns and other grassy areas to less than 6 inches (16 cm) greatly reduces the potential for human-tick contact. Of course, the environmental consequences of habitat modification must be thoroughly evaluated to avoid creating additional problems.

When environmentally acceptable, controlled burning has been shown to reduce tick abundance for six months to one year. Besides killing all active stages, burning reduces questing success by destroying the vegetation that is normally used to contact passing hosts. Success is dependent on several factors: amount of combustible brush and ground cover present, environmental and climatic conditions at the time of burning, size of the area to be burned, tick activity, and rate of tick reintroduction due to animal utilization. There must be a critical mass of combustible material to support an effective controlled burn, and its moisture content must be low enough to allow a thorough burn. It is best to burn in the late evening, when ambient humidity is higher and winds are minimal. These conditions favor a slower burn that consumes some of the protective ground cover and permits penetration of high temperatures to the lower levels of unburned cover or leaf litter. Burning when winds are high increases the risk of wildfire and greatly reduces the consistency and effectiveness of the controlled burn. Fires in areas less than 5 acres (2 hectares) generally provide only temporary reductions in tick numbers due to the rapid reintroduction of ticks by animals passing through the burned site or the reestablishment of animal populations in the burned area. Even large controlled burns may produce only a temporary decrease in tick populations. In some instances, if the amount of vegetation is not regulated, controlled burns may actually increase the browse available for deer and other animals, thus eventually increasing the tick population above pre-burn levels. Success in habitat modification is largely dependent on removal of ground cover, especially the mulch that shelters all tick stages. Burns can be conducted in winter, when trees are dormant, to avoid damage to timber resources. All burning must be coordinated through proper installation channels.

Simple mechanical clearing of underbrush, to the extent that it allows 70-80% sunlight penetration, has been shown to be an effective means of reducing numbers of Ixodes scapularis.

In developed areas, frequent mowing of grass will also definitely control tick populations. If mechanical clearing is accompanied by herbicide application, larval populations may be reduced by 90% and adult and nymphal populations may decline by 50% or more. Like burning, the success of this technique depends on various ecological, environmental, and control factors: amount of vegetation removed, size of the area, tick activity, extent of reinfestation due to animal utilization, and extent to which control procedures are maintained. Clearing also helps reduce the attractiveness of an area to small mammals, birds, and deer. As with controlled burns, the smaller the area cleared, the faster it is likely to be reinfested by ticks. In order to reduce tick populations to acceptable levels, vegetation control must be implemented on a regular basis. In most instances, control by mechanical means will be the preferred technique because it does not contaminate the environment with pesticides. However, this method is labor intensive and only slowly reduces tick populations. Another habitat modification technique is to thin early successional shrubs and grasses in early to mid fall, stressing the overwintering tick population and reducing survivability. This should be done late enough in the season that regrowth does not occur.

c. Acaricide Application

Use of an acaricide, or any other pesticide, must be consistent with label requirements of the Environmental Protection Agency (EPA) and the Federal Insecticide, Fungicide and Rodenticide Act of 1972, as amended. Outside the jurisdiction of the EPA, DoD Directive 4150.7 requires that pesticide application be in accordance with the accepted standards of the host country, or any host-tenant agreement between the United States and that country. In the absence of any host country standards and agreements, the application must be consistent with EPA requirements or the regulations of the respective service, whichever are more stringent. Beyond these requirements, pesticide selection and application should be in accordance with the recommendations set forth in AFPMB Technical Guide 24, “Contingency Pest Management Pocket Guide.” Chemical control can be accomplished by conventional ground application, aerial application, or both, but area chemical treatments should be a last resort in tick control operations.

Experience has shown that applications of liquid pesticides to control ticks may be impractical because of incomplete penetration of vegetation, especially when aerial dispersal is employed. However, adult Ixodes scapularis generally quest in the shrub and grassy layer after the autumn leaf drop and again in the spring before leaves appear. The lack of protective foliage during these periods makes adults of this species vulnerable to chemical sprays. Effective control of I.

scapularis in all stages has been achieved in small areas using a backpack sprayer or handoperated granule spreader, thereby also reducing environmental contamination of nontarget areas. But such applications are very labor intensive and unsuitable for larger areas. As well, small areas may require frequent retreatment because ticks may be quickly reintroduced by animal hosts. Seasonal applications of acaricides target overwintered nymphs as they become active in the spring and early summer, and possibly larvae in late summer or early fall. Large-scale applications using vehicle-mounted air-blast sprayers or aerial dispersal of liquid or granular pesticides have provided 50-90% control for 6-8 weeks. Generally, the more active ticks are, the better the control achieved with pesticides (tick activity usually stops when temperatures fall below 54oF or 13oC), and localized control provides only localized and temporary relief. When minimal resources are available, treating an area two weeks before it is to be used achieves maximum control for the effort expended.

The formulation (e.g., dust, granule, emulsifiable concentrate) is one of the primary considerations in selecting the type of equipment that will be used to apply an acaricide. In addition, the formulation may be a very important factor in limiting pesticide drift to nontarget areas and in determining the amount of time required before tick control is achieved. Normally, liquid formulations of pesticides provide immediate reduction in tick populations, while granular formulations require a few days before the pesticide is released from the granules into the ticks' habitat. Liquid formulations of pesticides can be applied to vegetation at various heights to kill questing ticks, whereas granular formulations only affect ticks at ground level. However, granular formulations are generally easier to apply and are less likely to contaminate nontarget areas through pesticide drift. In comparative studies, both formulations gave about the same level of control when evaluated over a period of 4-6 weeks. Several factors are associated with successful acaricidal tick control, including type of acaricide, ambient temperature, dosage, penetrability of canopy, extent of coverage, susceptibility of the tick species, and tick life stage and physiological condition.

In recent years, Agricultural Research Service entomologists at the Knipling-Bushland U.S. Livestock Insects Research Laboratory in Kerrville, Texas, have proposed an alternative to earlier acaricidal or medicated bait approaches for controlling such important vectors as Amblyomma americanum and I. scapularis. A passive topical treatment system called the "4-poster" attracts white-tailed deer to a food source and, as they feed, allows self-application of an acaricide, such as amitraz, to the head, ears, and neck to control ticks. Through grooming, acaricide is transferred to other body areas, such as the brisket, axillae, groin, and vent. The 4-poster has a central reservoir for whole kernel corn that fills two feeding/application stations at either end of the base. These stations each have a single feeding port adjacent to two vertical acaricide-impregnated applicator rollers. A horizontal plate partly obscures each feeding port and forces deer to rub against the rollers as they feed. The rollers permit treatment of both antlered and antlerless deer and allow upward retraction of the head if deer are startled while feeding. Preliminary field tests in Texas and throughout the Northeast Corridor have indicated that, at least locally, very high percentages of tick control are possible with this device.

d. Deer Exclusion

As with the 4-poster (above), the specificity of Ixodes scapularis for deer provides a point of vulnerability that may be exploited to reduce tick population size. Experience has shown that reducing the number of deer will not immediately reduce the number of ticks; instead, ticks “double up” on the remaining deer and, to some extent, utilize alternate hosts. Tick densities are not reduced immediately because of the long life cycle of three-host ticks. Following a reduction in deer density, populations of nymphs and adults will take one or two years to fall. Because deer provide over 90% of adult I. scapularis blood meals, eliminating deer, either by exclusion or removal, is ultimately an effective tick control measure.

A variety of fences (Fig. 2) have been developed to exclude deer, ranging from single electrified wires for areas where the deer population is low, to complex, multi-wired electric and nonelectric designs, required in areas where deer pressure is great. Fence selection and design are also strongly influenced by location, terrain, vegetation and cost. A 9-foot (3 m) high, woven-wire, non-electric fence has been used successfully to exclude deer from recreation areas. A 6-wire, vertical, high-tensile, electric anti-deer fence is effective in many situations. Voltage energizers of various capacities, which can electrify short or long runs of fence, are used to charge wires spaced so that deer cannot pass through without contacting them. The hot and ground return wire sequence can be changed with a switching device to provide the most effective shock for snow cover, tall grass, or very dry situations. Vegetation must be controlled with herbicides in a strip 12-18 inches (0.3-0.5 m) wide directly under the fence and by mowing for 5-8 feet (1.5-2.5 m) on the deer side of the fence to minimize voltage drops and to provide the deer with an approach zone. This zone allows deer to perceive the fence as a no-entry barrier that is to be avoided, and encourages a pathway around the fence rather than through it. Electric fences will also work without a mowed strip when conditions like rough terrain or dense timber make mowing impractical. Although electric fences are expensive, and require regular outlays for maintenance, vegetation control, and the costs of battery replacement and/or AC current, such fencing may be appropriate around residences and in selected recreational areas.

18 - Mitigation strategies of tick-borne diseases in domestic animals (graphs and simple actions) for citizens, veterinary professionals, and military personal

Habitat modifications to the landscape for tick control are designed to reduce tick densities, modify tick and host contact (e.g. equines, wildlife), and decrease pathogen infected ticks and hosts (Stafford et al. 2017). The main goal is to modify the habitat so that ticks are unable to survive and hosts are not attracted to the habitat. Ticks have habitat preferences that are often similar to their preferred hosts. The habitats have essential requirements for their survival including certain temperature and humidity ranges. Landscape changes can increase the sunlight and lower humidity so it is not hospitable to the ticks in the area. They can also be modified to reduce contact between ticks and their hosts in the vicinity. For example, you can remove grasses, twigs, and leaves of woody trees in an area, a food source in North Carolina that white-tailed deer thrive on in this southern State and a preferred host of the black-legged tick. The spatial scale and landscape need to be consider when implementing a habitat modification plan to determine areas that are likely to provide climatic conditions that can support high tick and host densities. Non-chemical modifications such as habitat modifications are often used as part of an integrated pest management plan for tick control and may include mowing grasses, removal of trees, reduction in shade by thinning trees, understory removal, and placement of mulch and barriers (Stafford et al. 2017, Piesman and Eisen 2008, Eisen and Dolan 2016).

Mowing

Reducing the vegetation by mowing is often used to decrease the height of a grasses that questing ticks commonly climb seeking hosts. Questing ticks can be found on a variety of vegetation including grasses, and shrubs. Ticks do not seem to have particular preferences as far as associated grasses or shrubs, but more often associated with host habitat preferences (Sonenshine 1991). The reduction in the height of vegetation changes the microclimatic conditions so that temperatures are warmer and humidity lowered affecting tick survival in the area. The American dog tick prefers humidity levels of 75% to 93% (Yoder et al. 2011). The vertical migration of ticks, survival of ticks on long and short substrates, and exposure to hosts in short and long grassed areas was conducted by a group in South Africa. Fourie et al 1996 determined that ticks tended to survived longer on the longer rods and sheep exposed to longer grass were infested with twice as many ticks as compared to the sheep exposed to ticks in shorter grass pens. Therefore, mowing can effectively reduce tick populations in an area and tick-host contact.

Mulch Barriers, Tree, Leaf Litter, and Understory Removal

Mowing, understory removal, livestock pasture rotations have been frequently used to decrease tick populations and tick-host contact for centuries; however, the concept of habitat management was reemphasized when Lyme disease appeared in the United States in the 1980's (Piesman and Eisen 2008). The blacklegged tick transmits Borrelia burgdorferi, the causative agent of Lyme disease so many studies have been conducted to determine the best integrated pest management approaches to reduce blacklegged tick populations. Schulze et al, 1995 indicated that leaf removal underneath trees reduced Ixodes scapularis nymphs by 75% in March, post 15 week treatment and 77% in June, two weeks after the treatment. The amount of leaf litter is a good predictor of tick abundance in an area (Adalsteinsson et al 2016). Brush removal was also effective in decreasing blacklegged tick populations (Wilson 1986).

Wood chip, tree bark mulches, and gravel can act as a buffer to reduce the number of ticks in the area and prevent ticks from migrating from a woodland area to pastures or lawns. Alaska yellow cedar sawdust borders placed between woodlands and lawns was effective in decreasing black-legged tick dispersal to the residential lawns (Piesman 2006; Eisen and Dolan 2016).). The mulch barriers can also suppress weeds and retain soils in the areas to decrease tick movement (Piesman and Eisen 2008).

Trimming tree branches and thinning overall structure of large trees allows for sufficient sunlight to penetrate the understory to create an unsuitable habitat for ticks by lowering humidity levels. Hubalek et al 2006 compared the number of questing Ixodes ricinus ticks along a forest trail that had been cleared of understory shrubs, small tree removal, and leaf litter removed, and ground vegetation to an uncleared forest transect. Ixodes ricinus nymphs were 3.4 times, 1.9 times, and 1.2 times less frequently collected over a three year period respectively (2003, 2004, 2005) in the cleared forest as compared to the uncleared forest. Ixodes ricinus adults were 27.2 times (year 2003), 4.0 times (year 2004), and 2.2 times (year 2005) less frequently recovered in the cleared forest as compared to the uncleared forest indicating the removal of understory vegetation and ground and sunlight exposure decreased tick abundance on the trails. In addition, mowing, clearing understory, and opening of tree canopy in oak-hickory woodlands in the United States reduced lone star tick larval density by 72%, nymphal density by 53%, and adult densities by 75% over a two year period (Hair and Howell 1970). Mount (1981) indicated that clearing vegetation in upland oak-hickory woodland reduced lone star tick larval densities by 84%, nymphal densities by 93%, and adult densities by 77%. Decreased soil moisture and relative humidity plus higher ground level temperatures are factors that likely limited lone star tick survival and egg hatching after vegetation was cleared. Habitats play an essential role in providing supportive humidity levels, moderation of sunlight, and regulating temperatures for both survival and egg development.

Acaricide Applications to Vegetation

Chemical applications should focus on control earlier in the seasonal questing activity of ticks. They are generally effective in reducing tick densities and tick-host contact. The seasonal timing of acaricide applications and habitat location are important in order to have the greatest impact on the various developmental tick stages on and off the host. If the tick species of interest is a three host tick, then the tick species spends most of its time off the host than on the host. The application of acaricides to tick habitats, such as woodland edges and grassy patches are important to reduce three host tick populations. The sprays should be applied during times that correspond to times when ticks are most actively seeking hosts. The single tick control method of acaricide vegetation treatments can have limited effects on creating an unsuitable habitat for ticks because of dense vegetation such as leaf litter. Complimentary acaricide treatments for hosts and habitat are more effective in reducing tick populations (Schulze et al. 1994).

There are a variety of acaricides used to control ticks, but synthetic pyrethroid insecticides are the most commonly used control agents. All chemicals used as insecticides or acaricides must be registered with the U.S. Environmental Protection Agency (EPA) and must be approved for area wide use or for use on a specific host species so check the labels for uses on hosts and habitats. These acaricides have been effective in controlling blacklegged tick and brown tick populations. Synthetic pyrethroids were highly effective in controlling Ixodes scapularis ticks in the northeastern states and when applied to a forest bordered lawn killed 95% of the host seeking nymphs (Schulze et al, 2001). In the laboratory, nymphal I. scapularis crawling on landscape stones treated with pyrethrin-based desiccants and insecticidal soaps suffered greater than 88% mortality. The use of Bayer Advanced Multi insect killer containing 0.4% beta-cyfluthrin and 0.7% imidacloripid was applied to yards of a community in Arizona infested with brown dog ticks. The residents saw a decrease in the number of ticks observed in the yards, Thirteen percent of the residents reported seeing ticks in their yards in 2012 and after treatment only 6% of the residents reported seeing ticks in their yards in 2013 (Drexlar et al. 2014). Stafford and Allan (2010) used the pyrethoid, bifenthrin, with a high sprayer in a residential setting and reduce the black legged tick nymphal stage by 86% with a single treatment in the month of May. In contrast, Rand et al 2010 reduced the blacklegged nymphal stage by 100% treating a woodland setting in the month of July with bifenthrin. There a variety of pyrethoids that have been found to be effective in the reduction of Ixodes scapularis tick populations in a variety of studies from a reduction of 85% to 100% (Eisen and Dolan, 2016).

Acaricide Applications to Wildlife Hosts and Host Exclusion

The use of chemical application on wildlife hosts should be consider in relation to the host diversity in the area as this may affect how well the wildlife host-targeted intervention may work as it differs between host species (Ginsberg 2001, Eisen and Dolan 2016)). This will be most effective with high density meso-predator hosts such as raccoons and opossums that have high tick burdens or large mammals such as white-tailed deer. Mesopredators can be given ivermectin treated feeds at bait stations set away from stabling areas. Deer can be passively treated with topical acaricide dipped rollers through the use of “four-posters” (Pound et al. 2000). Given the size of the facility and the amount of high quality wildlife habitat surrounding the area any attempt to fully exclude wildlife or provide acaricide treatments to rodents or lagomorphs would not be effective.

Integrated Tick Management Approach

Tick control has many limitations due to the complexities of tick ecology and transmission of tick-borne diseases (Torres 2015). In general, single intervention tick control strategies are only as effective as the duration of the method used (Stafford et al 2017). For example, the regrowth of vegetation will reintroduce suitable habitats for ticks and acaricides generally have efficacies that are reduced as time passes or climate changes (e.g. dilution from rainfall). Therefore, multiple tick control strategies based on tick ecology that are a part of an integrated pest management plans are important to consider when attempting to increase the chances of reducing tick populations and tick-host contact. The implementation of multiple tick control methods has been proven to be more effective than single control strategies. Lone star tick populations were reduced in a non-agricultural area when different tick control methods were combined. The combination of mechanical vegetation management and application of acaricides to the vegetation reduced the lone tick populations by 94% whereas host exclusion (white-tailed deer) and acaricide application reduced the tick populations by 89%. The largest effect on the reduction of the lone start tick population was the use of three methods including acaricide applications, host exclusion, and reduction of vegetation with 96% tick population reduction (Bloemer et al 1990). Schulze et al 2008 used three different methods to decrease black-legged tick populations in a residential area in New Jersey. He used four-poster method that used invermectin treated corn to treat white-tailed deer, rodent bait boxes, and barrier applications of granular deltametrhin, a pyrethroid ester. The number of black-legged ticks were reduced on white-footed mice by 92.7% and 95.4% for larvae and nymphs respectively. The number of host seeking ticks was reduced by 90.6% for larvae, 94.3% for nymphs, and 87.3% for adults. Drexlar et al 2014, used an integrated tick control plan to reduce Rocky Spotted Fever cases in an Arizona community. It involved both the use of tick collars on dogs and spraying acaricides on yards. Using this approach, they saw a reduction of the ticks in the area and RMSF cases. More than 51% of dogs in the area were infested with ticks and after treatment, they saw fewer 6% of the dogs infested a year later. The integrated management approaches are likely to be the best plan to use for effective tick control and reduction in the transmission of tick-borne diseases in this area.

19 - Mitigation strategies of tick-borne diseases in wildlife (graphs and simple actions) for citizens (hunters), veterinary professionals, wildlife biologists, military personal.

The wildlife-livestock-human interface is a driver for increased tick densities resulting in a greater prevalence of tick-borne disease cases. Check these references:

Vector Borne Zoonotic Dis. 2018 Jan;18(1):55-64. doi: 10.1089/vbz.2017.2146. Epub 2017 Nov 27.

Prev Med Rep. 2018 Nov 13;13:16-22. doi: 10.1016/j.pmedr.2018.11.004. eCollection 2019 Mar.

Ann Agric Environ Med. 2018 Jun 20;25(2):360-363. doi: 10.26444/aaem/89919. Epub 2018 May 17.

Telford, S. R. 2017.Deer reduction is a cornerstone of integrated deer tick management. Journal of Integrated Pest Management 8: 25.https://doi.org/10.1093/jipm/pmx024

Parasit Vectors. 2014 Jun 25;7:292. doi: 10.1186/1756-3305-7-292.

J Econ Entomol. 2012 Dec;105(6):2207-12.

Although conventional habitat-targeted acaricide applications have proven to be the most efficient and reliable means of suppressing host-seeking tick populations (Stafford and Kitron 2002; Schulze et al. 2005, 2008), the use of pesticides has met with growing public concerns over potential health issues and adverse environmental impacts (Ginsberg 1994, Schmidtmann 1994, Gould et al. 2008). Consequently, the development of effective and environmentally acceptable alternative tick control strategies has become an important public health initiative (Stafford and Kitron 2002, Hayes and Piesman 2003, Dolan et al. 2004).

Host-targeted tick control may offer an alternative to area application of acaricides (Schulze et al. 2007). In 1999, the Centers for Disease Control and Prevention (CDC) began testing a bait box to control subadult Ixodes scapularis Say on small mammal reservoir hosts to reduce the incidence of Lyme disease (Dolan et al. 2004). In 2002, a bait box incorporating the results of these experimental trials became commercially available as the Maxforce Tick Management System (TMS; Bayer Environmental Science, Montvale, NJ). However, poor performance of the original 2002 version of the bait box required changes in wick design and bait formulation. A trial of improved Maxforce TMS bait boxes in New Jersey during 2004–2005 resulted in 92.7% and 95.4% reduction in nymphal and larval tick burdens, respectively, on white-footed mice (Peromyscus leucopus Rafinesque) and eastern chipmunks (Tamias striatus L.), after single 4-wk deployments (Schulze et al. 2007).

Although results of this field trial were promising, between 36.4% and 92.0% of the bait boxes deployed were damaged by eastern gray squirrels (Sciurus carolinensis) Gmelin; Schulze et al. 2007, T. L. Schulze, unpublished data), which compromised the child-resistant status of the boxes and often rendered the product label illegible. These problems were contributing factors in the eventual withdrawal of Maxforce TMS from the market in 2006. Subsequently, Tick Box Technology Corporation (Norwalk, CT) acquired the rights to manufacture and market the bait boxes as SELECT Tick Control System (TCS) in 2012. The new box was equipped with a two-piece metal protective covering to prevent squirrel damage. In this trial, we evaluated the ability of SELECT TCS to reduce the abundance of host-seeking I.scapularis, as well as the effect of the protective cover on acceptance and use by targeted small mammals and its ability to prevent or minimize damage and disturbance by nontarget wildlife.

The study describes a 2-yr trial to evaluate the ability of SELECT Tick Control System (TCS) host-targeted bait boxes to reduce numbers of host-seeking Ixodes scapularis nymphs in a residential neighborhood. After four successive 9-wk deployments, nymphal and larval I. scapularis infestation prevalence and intensity were significantly reduced on target small mammals. In addition, these deployments resulted in 87.9% and 97.3% control of host-seeking nymphs in treatment sites at 1 yr and 2 yr postintervention, respectively. Installation of a protective metal cover around the SELECT TCS bait boxes eliminated nontarget wildlife damage to bait boxes that resulted in failure of previous bait box types.

Bait Box Description

SELECT TCS consists of a 19.05- by 13.97- by 6.35-cm child-resistant, injection-molded plastic box that houses a bait attractant and a fipronil-treated felt wick placed so that small mammals entering a box are passively treated by contacting the wick while attempting to reach the bait. In laboratory trials, a single topical treatment of 0.75% fipronil effectively protected mice from being bitten by I. scapularis nymphs for 4–6 wk (Dolan et al. 2004). SELECT TCS bait boxes were fitted with a two-piece, tightly fitting protective cover constructed of 0.032 gauge galvanized steel. The top and bottom sections of the protective cover and bait box were secured together at two opposite corners by means of 20.3-cm cable ties (Thomas & Betts Corp., Memphis, TN).

These results demonstrate that SELECT TCS may provide a significant reduction in exposure to host-seeking ticks, while reducing the use of pesticide compared with traditional area-wide chemical control. But, because the bait boxes target only specific life stages within the 2-yr life cycle of I. scapularis and kill only ticks that have already acquired a host, significant reduction of the tick population is not realized until months or years after deployment. This has important implications for host-targeted methods because their inherently delayed efficacy results in significant risk of exposure to I. scapularis nymphs well after initial deployment. Such lag-times may affect their widespread public acceptance and commercial use that requires that significant tick control must be achieved more rapidly (Schulze et al. 2007).

Nevertheless, bait boxes offer several other benefits. Because they reduce the number of subadult ticks feeding on reservoir competent hosts, the bait boxes have the potential to both reduce the force of infection (defined as the number of secondary infections arising from a focal infection, Eisen et al. 2012) and reduce infection prevalence in host-seeking ticks (Dolan et al. 2004).

More information is also needed to assess how the presence and abundance of alternate hosts (and alternate reservoir hosts) in residential situations may affect the efficacy of bait boxes (Eisen and Dolan 2016). For example, shrews are recognized reservoirs for B. burgdorferi and have been shown to use bait boxes (Ostfeld 2011), but are not effectively sampled by the methods employed here. Capture data indicate that such hosts are present and may be present in significant numbers (Schulze et al. 1986, 2005, 2007). Future research on host-targeted tick control should include efforts to examine mammal community composition and the roles played by reservoir and refractory hosts in residential situations. Also, any host-targeted approach to tick control that relies on attractive food baits effectively provides a supplemental food source to the host population, which may have consequences for local host density and, ultimately, disease transmission dynamics (Ostfeld et al. 2006).

SELECT TCS appears to offer an effective alternative, delayed efficacy notwithstanding, to the use of area application of acaricide in residential situations. Further research, to include analysis of disease infection prevalence in hosts and ticks, is required to verify the potential for tick-borne disease risk reduction indicated here. In addition, research is needed to determine what proportion of host small mammals using treated properties is actually treated by bait boxes. This may have important implications not only for efficacy, but also in determining cost of deployment. Ultimately, however, tick control efforts in residential areas, particularly any integrated tick control program that may combine multiple habitat and host-targeted methods, must consider the ecology of what remain as yet poorly understood suburban and ex-urban ecosystems in order to achieve comprehensive, reliable, and environmentally responsible reductions in tick-borne disease risk

Reference: Terry L. Schulze, Robert A. Jordan, Martin Williams, Marc C. Dolan, Evaluation of the SELECT Tick Control System (TCS), a Host-Targeted Bait Box, to Reduce Exposure to Ixodes scapularis (Acari: Ixodidae) in a Lyme Disease Endemic Area of New Jersey, Journal of Medical Entomology, Volume 54, Issue 4, July 2017, Pages 1019–1024

Simple tips for Tick prevention for hunters that uses dogs and horses:

To protect your dogs, you should consult your veterinarian, but basic guidelines include:

Apply topical or systemic tick-control treatments. Consult your veterinarian about the appropriate product for your dog.

If possible, limit access to tick-infested areas.

Check dogs frequently for ticks or, at a minimum, at the end of each day's activities. The ticks should be promptly and carefully removed.

To protect your horses, you should consult your veterinarian, but basic guidelines include:

Apply topical insect repellent products. It is likely you will have to reapply the products regularly, especially if you are traveling through areas with high insect activity.

If possible, limit access to tick-infested areas.

Check horses frequently for ticks or, at a minimum, at the end of each day's activities. The ticks should be promptly and carefully removed. Be sure to check the tail, mane and ears thoroughly for ticks.

Consider the use of insect nets designed to be worn over horses' eyes and ears to minimize insect bites, but do not consider them 100% effective. If you use these products, you should still check your horses regularly for ticks.

Source: American Veterinary Medical Association (AVMA)

DISEASE PRECAUTIONS FOR HUNTERS (AVMA)

https://www.avma.org/public/Health/Pages/Disease-Precautions-for-Hunters.aspx

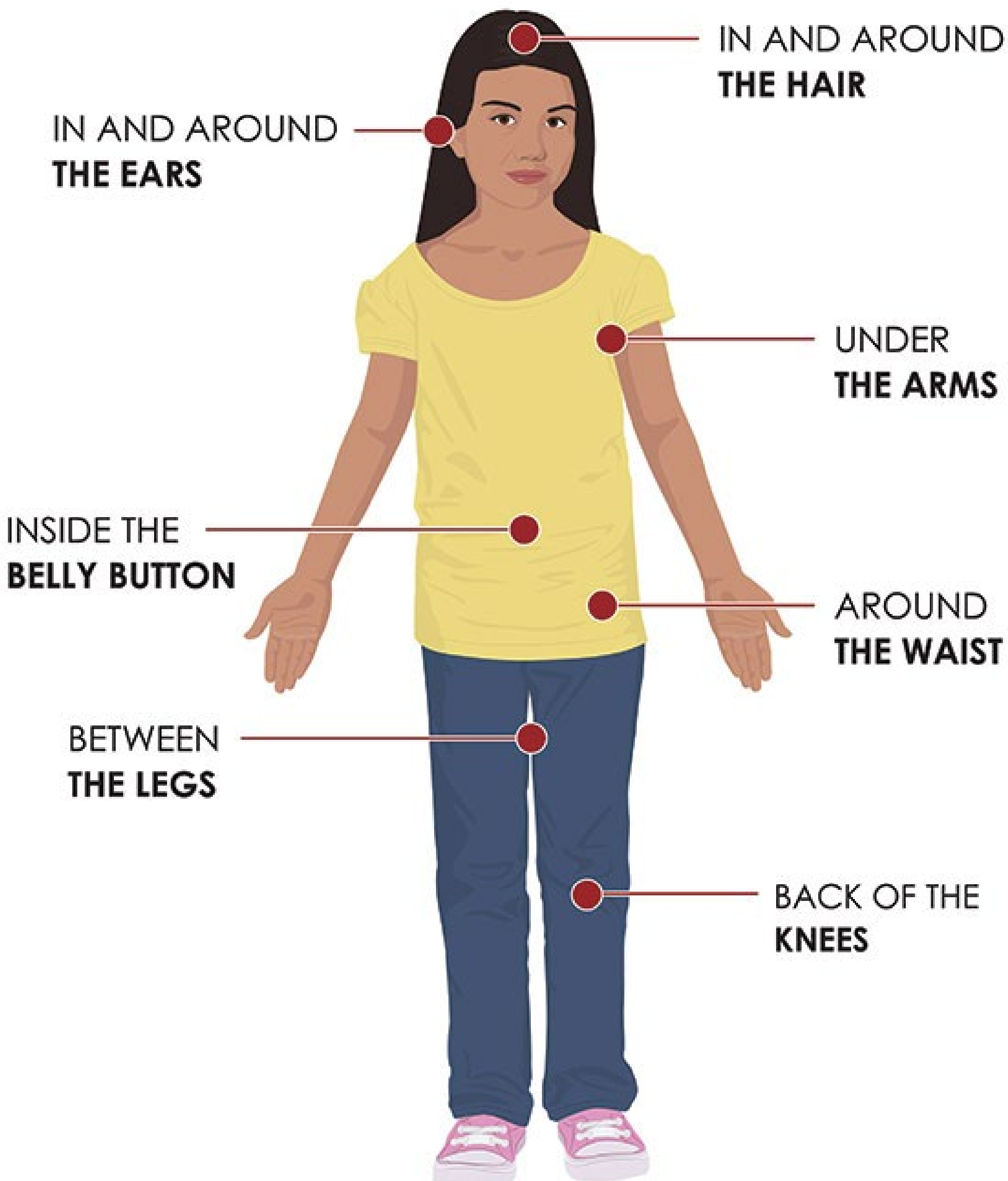
Companion vector-borne diseases: http://www.cvbd.org/en/tick-borne-diseases/

Source: CDC

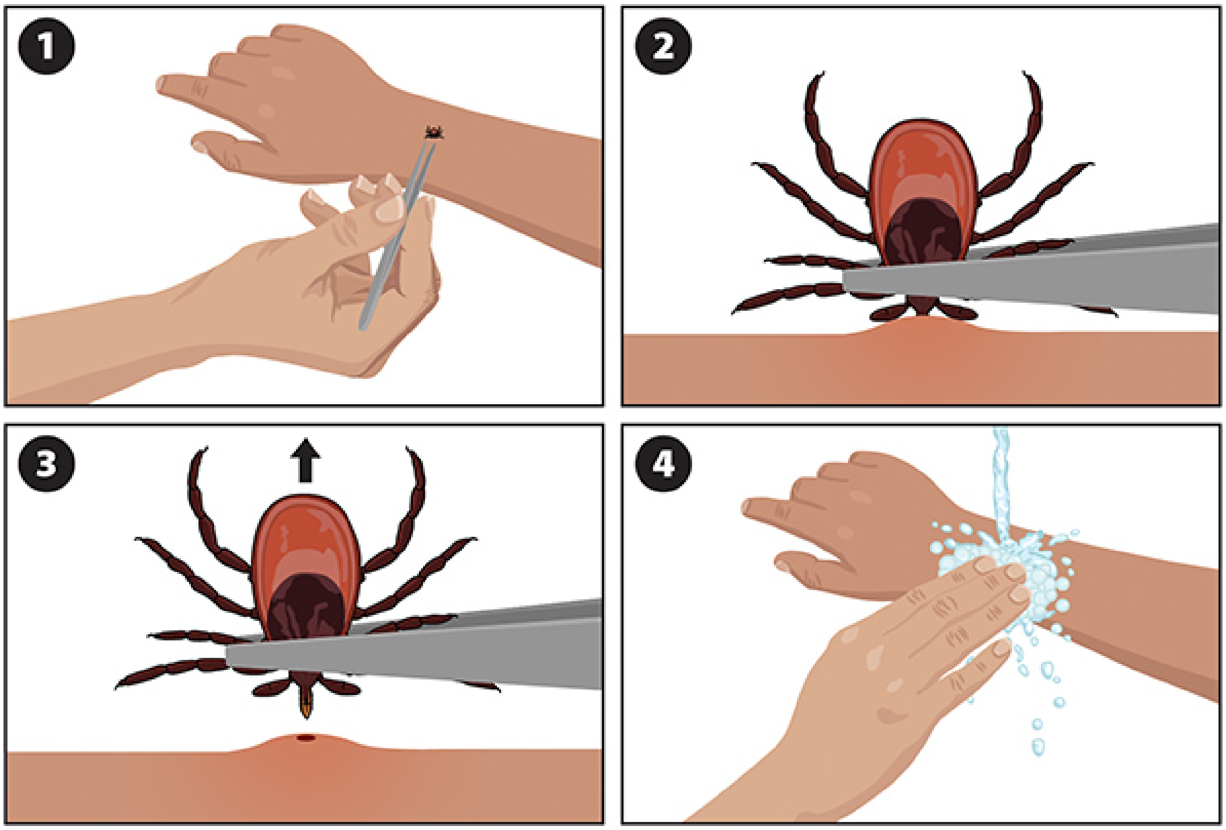
Check your body for ticks after being outdoors. Conduct a full body check upon return from potentially tick-infested areas, including your own backyard. Use a hand-held or full-length mirror to view all parts of your body. Check these parts of your body and your child's body for ticks:

- **Under the arms**
- **In and around the ears**
- **Inside belly button**
- **Back of the knees**

- **In and around the hair**
- **Between the legs**
- **Around the waist**



Source: CDC



Source: CDC

Contributor: Peach Van Wick, DVM (WCV)

In order for a population of ticks to thrive, three factors must be present: the ticks, their hosts, and a suitable environment. When considering wildlife as part of this triad, some species help with tick control whereas others can assist in perpetuating the problem. Species such as Virginia opossums and Eastern gray squirrels are known to consume a variety of ticks; therefore, land that is managed to promote good habitat for these species may result in an overall decreased number of ticks in a particular area.[1] Other species, such as white-tailed deer,

that serve as the definitive hosts for ticks that carry harmful pathogens, may be less desirable in particular settings, especially where interaction with domestic animals and humans is more likely.[2] One study in Connecticut demonstrated a decline in the number of ticks in a certain geographical area following the reduction of the white-tailed deer population.[3]
A number of control methods have been attempted in areas with healthy white-tailed deer populations. One example is a free-standing bait station that delivers a topical, anti-parasitic medication on the deer that come to feed.[4,5] Though proven to be moderately effective on deer that regularly use the bait stations, this method promotes congregation of deer around a specific site which can result in the spread of other pathogens such as chronic wasting disease, brucellosis, etc.

Another example of a control method against ticks on white-tailed deer is the systemic administration of an antiparasitic medication, ivermectin, delivered in treated feed.[6] This method also promotes congregation of deer and other non-target species. Additionally, medicated feed intended for free-ranging wildlife should be used judiciously due to the concern of parasitic resistance and potential negative effects on non-target arthropods. While both methods could be effective in the appropriate setting, neither is likely to result in large-scale tick control in wildlife species of concern.

Perhaps a more feasible solution for tick control would be best achieved as preventative and protective measures taken with pets, livestock, and humans.

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2. Paddock CD, Yabsley MJ. (2007) Ecological Havoc, the Rise of White-Tailed Deer, and the Emergence of Amblyomma americanum-Associated Zoonoses in the United States. In: Childs J.E., Mackenzie J.S., Richt J.A. (eds) Wildlife and Emerging Zoonotic Diseases: The Biology, Circumstances and Consequences of Cross-Species Transmission. Current Topics in Microbiology and Immunology, vol 315. Springer, Berlin, Heidelberg.
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Contributor: Peach Van Wick, DVM and Ernesto Dominguez, DVM (WCV)

Ixodes tick control (including habitat management through burning, the use of acaricides, and white-tailed deer elimination) has been shown to reduce Ixodes scapularis populations by up to 94%, and acaricide application to deer decreased nymphal I. scapularis populations by up to 83%. However, the effect of these strategies on the incidence of Lyme disease in human beings remains unknown.

Control efforts for Babesia sp. vectors rely on culling wild ungulates in infected and neighbor farms in conjunction with acaricide control of tick infestations in the area. The systematic culling of white-tailed deer as a tick eradication method is regarded as unfeasible due to its high cost, regulations preserving wildlife in American Indian reservations and the ethical considerations behind this approach. Pasture rotation methods to reduce the tick burden initiated in the 1970s appear to have failed due to the abundance of white-tailed deer and other wild ungulate species .

Two other methods to control ticks on white-tailed deer exist: acaricides and vaccination. Acaricides include systemic treatments through the consumption of ivermectin-medicated corn and/or topical treatments using 4-poster deer treatment bait stations and/or 2-poster deer treatment feeder adapters, both of which passively apply acaricide topically to deer . Vaccines against cattle ticks became available in the early 1990s as a cost-effective alternative for tick control that reduced acaricide use as well as the associated problems such as the selection of acaricide-resistant ticks, environmental contamination and the contamination of milk and meat products with acaricide residues. Vaccination trials with commercial vaccines containing the Rhipicephalus microplus BM86 and BM95 gut antigens, Gavac® and TickGARD® (Heber Biotec S. A., Havana, Cuba and Hoeschst Animal Health, Australia), reduced the number of engorging female ticks, their weight and their reproductive capacity, thus resulting in the reduction of tick infestations and in the prevalence of some tick-borne pathogens. Other candidate protective antigens such as subolesin (SUB) have recently been proposed for the control of different tick species and other ectoparasites. Vaccination with BM86 and SUB tick protective antigens have reduced tick infestations in red deer (Cervus elaphus) and white-tailed deer with an overall vaccine efficacy of approximately 80% for the control of R. microplus infestations in white-tailed deer.

Wildlife Population Control

Many factors contribute to the natural regulation of wildlife abundance. Herbivores, which are likely to be particularly relevant for shared disease maintenance, are probably limited by food availability and predation or hunting harvests. Disease itself is a mechanism that may regulate wildlife populations. The problem of overabundant wildlife populations and thus, an increased reservoir population, may occasionally be addressed by using relatively simple management actions such as feeding bans or increased harvesting.

It has been demonstrated that the supplementary feeding of red deer has a strong effect on the reproductive success of hinds, and hence on population productivity. However, feeding bans will have little to no effect on overabundant populations that are not provisioned, such as those in protected areas. Feeding bans have been known to generate conflict with hunters and landowners if baiting and feeding is perceived as a traditional and rewarding practice by which to increase the hunting harvest or other perceived values (e.g., deer as a symbol of natural resources for Michiganders.

The total elimination of a reservoir species is impractical, expensive, and ethically and ecologically unacceptable unless it targets an introduced species.

Moreover, hunting has limitations in its ability to control wildlife populations, for example, in protected areas or urban habitats, and the effects of culling are only temporary if population control is not sustained over time. It is also known that eliminating or substantially reducing the number of abundant species can have indirect effects on other species. For instance, fox numbers increased after badger culling for TB control in the UK; and deer and moose (Alces alces) numbers increased, as well as grazing pressure and habitat damage, when carnivore culling was conducted in Canada. Culling also has effects over the targeted species such as increased movement due to social disruption [dispersal and immigration] and compensatory reproduction. The aforementioned reasons have led some authors to state that culling reservoir populations in order to mitigate or control the transmission of pathogens has proven disappointingly inefficient and EFSA to advise against the wild boar mass culling carried out to control ASF transmission in some EU member states.

Reference: Citation: Gortazar C, Diez-Delgado I, Barasona JA, Vicente J, De La Fuente J and Boadella M (2015) The wild side of disease control at the wildlife-livestock-human interface: a review. Front. Vet. Sci. 1:27.