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Deer Reduction Is a Cornerstone of Integrated Deer Tick Management

Sam R. Telford, III

Department of Infectious Disease and Global Health, Tufts University Cummings School of Veterinary Medicine, 200 Westboro Road, North Grafton, MA 01536 (sam.telford@tufts.edu)

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Abstract

Deer reduction must be considered in any discussion of effective community level intervention to reduce the risk of Lyme disease. There were three main factors that allowed the epidemic to emerge (reforestation, suburbanization, and dense deer herds). Only deer density may be targeted in efforts to reduce, over the long term, the risk landscape to what it was prior to the epidemic. The majority of studies analyzing the effect of deer reduction as a mode of intervention against Lyme disease demonstrate great reductions in the density of deer ticks, a prerequisite for local risk for acquiring infection. Zoonotic transmission of the deer tick microbial guild requires tick reproduction and infection of the resulting ticks. Deer reduction targets tick reproduction without which there is no enzootic transmission cycle. Arguments against the utility of deer reduction as a mode of intervention mistakenly conflate its potential efficacy with the sociopolitical obstacles for implementing such an action. In addition, some confusion exists as to the goals of deer reduction as a mode of intervention: it will not reduce risk in the short term over large areas, but is intended to reduce risk over time and in discrete sites. Deer reduction would be most effective as part of an integrated tick management program that comprises short-term and long-term approaches.

Key words: deer ticks, Lyme disease, deer reduction, integrated tick management

Lyme disease is the most common vector-borne infection in the United States and in much of the European Union. This bacterial zoonosis is due to a spirochete (*Borrelia burgdorferi* sensu lato) transmitted by deer ticks (a common name not on the ESA-approved list of names which I use herein to refer to the American clade of *Ixodes scapularis*) or other ticks of the *Ixodes persulcatus* species complex. Although easily treatable in the acute stage by oral antibiotics, failure to detect and treat acute disease may lead to chronic sequelae, including Lyme arthritis and neuroborreliosis. Lyme disease was initially restricted to coastal sites in southern New England, New York, and New Jersey, as well as foci in the upper Midwest, but has expanded its distribution greatly over the last 2 decades. About 30,000 cases are reported each year, but it is recognized that this represents a 5–10-fold under-reporting (Hinckley et al. 2014) and the annual incidence in endemic sites is about 1–3% as measured by prospective studies. Deer ticks maintain a microbial guild including the agents of human babesiosis (*Babesia microti*); human anaplasmosis/granulocytic ehrlichiosis (*Anaplasma phagocytophilum*); Borrelia miyamotoi disease; and deer tick virus or Powassan virus lineage II (Telford and Goethert 2008), all of which increasingly affect people of the eastern United States. Despite the availability of a wide range of interventions that may reduce risk, incidence continues to increase. In part, the public may be confused by the array of choices, but it also does not help that there is no scientific consensus about the efficacy of the various modes of intervention. Indeed, some peer-reviewed reports (Jordan et al. 2007, Levi et al. 2015, Kugeler et al. 2016) have concluded that an important environmental intervention, deer reduction, has not been proven to reduce human Lyme disease risk or that its utility is restricted only to island sites. This commentary argues that it is premature for such conclusions and that deer reduction should be a cornerstone of integrated tick management.

Public health interventions need to be defined a priori so that limited resources and energy are efficiently used. Interventions may comprise short-term approaches that require constant effort and resource. As a clear example of short-term intervention, the application of *Bacillus thuringiensis israelensis* as a larvicide to control aedine or culicine mosquitoes must be done periodically each transmission season; if the intervention is removed, mosquitoes become dense very quickly. Source reduction, via habitat management, seeks to minimize the capacity of the local environment to sustain intense mosquito breeding and is thus a long-term strategy. Once accomplished, source reduction requires only a maintenance effort in subsequent years. Short-term methods should be complemented with long-term methods in integrated management programs, the former reducing risk while the latter are put in place. It would be unethical to wait for a long-term method to work and do nothing to prevent infection in the interim.

Short-term approaches to reduce the risk of bites by ticks infected with Lyme disease spirochetes include application of acaricides to vegetation so that discrete sites might be rendered less risky for a few weeks or months. Personal protection is also a short-term approach. Combinations of short-term approaches such as the use of 4-poster acaricide stations to treat deer, rodent bait boxes, and application of acaricides to vegetation can be very effective in reducing the density of host-seeking ticks (Schulze et al. 2007, 2008). However, ceasing the application of these methods is likely to be followed by a quick return to preintervention conditions. No lasting effect is expected; effort and resources must be expended every transmission season forevermore.

Long-term approaches target communities or larger aggregations of individuals, over a generation or more, seeking to promote better health on a permanent basis. Lyme disease emerged as a public health burden over half a century in the northeastern United States due to a convergence of factors relating to habitat structure (abandonment of farmland and successional regrowth of forest); habitat encroachment (development for housing or recreation); and burgeoning deer density (Spielman et al. 1985). Sites that are currently intensely zoonotic might be restored to their pre-1960s state of lesser risk by promoting more open, nonwoodland landscapes; removing human habitations and preventing land development and use by humans; and by reducing deer herds to the densities that were apparent prior to the 1960s. Of these three targets, only deer density might be realistically manipulated. The goal of deer reduction is to improve the public health over the long term, with progressively less invested in effort from the community. It would be illogical to expect that even eradicating deer in a community this year would lead to fewer Lyme disease cases next year. The deer tick has a 2-yr life cycle (Yuval and Spielman 1990) with inactive or diapausing instars that would emerge to seek hosts in the next transmission season even if the reproductive bloodmeal source became scarce. Note that this is in the absence of other measures. If deer were greatly reduced in year 1, followed by acaricidal spraying in spring and late summer of year 2, there might be a reduction in risk during year 2 and certainly in year 3 and subsequently. Such an intervention design demonstrates the potential power of an integrated tick management approach.

Targeting the reproduction of the deer tick is more effective than reducing the survival and development of subadult stages. Each adult female deer tick that feeds successfully will lay as many as 2,000 eggs (Balashov 1972 for the related *Ixodes ricinus*). Although the actual proportion may vary depending on the local medium sized and large mammal representation, a very large proportion of all adult deer ticks feed on deer (Wilson et al. 1985, Wilson, Litwin, et al. 1990). Thus, removing a main source of the reproductive bloodmeal should reduce the density of deer ticks. One might suggest reducing the density of mice, chipmunks, or certain birds to reduce the chance that larvae and nymphs will feed on them and develop further (and also become infected), but killing one fed adult female deer tick is equivalent to killing 2,000 larvae or several hundred nymphs. It might be argued that without subadult development, there would be no adult ticks but the successful feeding of a single female tick would compensate for great subadult tick mortality. Then too, although we focus on the deer ticks and their microbial guild, Lone Star ticks are sympatric throughout much of the deer tick distribution and appear to be invading northward (Paddock and Yabsley 2007), with some established populations as far north as southeastern Massachusetts and sporadic infestations even in Maine. Lone Star ticks maintain their own microbial guild and transmit a set of zoonotic infections: Masters' Disease/STARI; human monocytic ehrlichiosis; *Ehrlichia ewingii* ehrlichiosis; Rocky Mountain spotted fever; and tularemia (Childs and Paddock 2003; Telford and Goethert 2008). Elsewhere in the United States, Lone Star ticks have been incriminated as vectors for recently identified hemorrhagic fever viruses (Bourbon virus, Heartland virus; Pastula et al. 2014, Kosoy et al. 2015, Godsey et al. 2016). Lone Star ticks mainly feed on deer in each of their life stages (Bishopp and Trembley 1945, Bloemer et al. 1986) and a single fed female may lay 3,500 eggs (Barnard 1990). Deer reduction (or their treatment with '4 posters'; Pound et al. 2009) may reduce dense infestations of Lone Star ticks, or prevent them from becoming established. At least in New England, the main bloodmeal source for mammal feeding mosquitoes, including those that are bridge vectors for eastern equine encephalitis or West Nile virus, or those that transmit diverse California encephalitis group viruses, is the white tailed deer (Molaei et al. 2008). The 'deer fly' (*Chrysops* spp.) also appears to depend on deer. Accordingly, deer reduction may have multiple public health and nuisance abatement benefits.

The evidence that reducing deer density will reduce tick density is strong (Telford 2002, Kilpatrick et al. 2014; see summary tables in Levi et al. 2015 and Kugeler et al. 2016) and that evidence does not need to be repeated here. In addition, acaricide treatment of deer or fenced exclusion plots also support the causal relationship between deer density and that of deer ticks (Daniels et al. 1993, Stafford 1993, Pound et al. 2009). As with any ecological experiment, outcomes counter to the more frequently detected outcome are evident but may have alternate interpretations or explanations. The Bernards Township project (Jordan et al. 2007) halved deer density from an astonishing 45/km^2 to 24/km^2, with little effect on tick density, but the observed endpoint deer density is still an order of magnitude above what would be required to expect any reduction in Lyme disease risk, empirically estimated at 3–5/km^2. This threshold is based mainly on the Great Island experiment and reflects a typical transmission scenario with the full New England mammalian fauna (Wilson et al. 1988, Telford 1993). Based on their experience, Jordan and colleagues suggested that deer reduction would not be cost effective or logistically possible for mainland sites, and hence this mode of intervention would only be suited to insular locations. There is some misinterpretation evident in assertions that the only successful experiments have been done on islands. Great Island, Bluff Point, Mumford Cove, and the Crane Reservation (Wilson et al. 1984, Deblinger et al. 1993, Stafford et al. 2003, Kilpatrick et al. 2014) all actually comprise peninsulas (tombolos) connected to the mainland and deer can and do move in and out of these sites, as they would a mainland site. Deer reduction could be locally maintained in part because deer shift their core home range areas away from where there is hunting pressure (Kilpatrick and Lima 1999, Hyngstrom et al. 2011) and hence targeted deer removal every year might not only keep the herd to a certain density as well as largely restricted to dense forested patches where people are less likely to intrude and encounter ticks.

The feasibility and logistics of an intervention should not be conflated with its efficacy. Deer reduction, in which deer are reduced to as close to the threshold of fewer than 5/ km^2, has biological efficacy. Whether community motivation or resources would allow for the intervention to be implemented and maintained is another question entirely. The same argument could be applied to deer-targeted acaricides ('4 posters'; Pound et al. 2009): these devices reduce host seeking ticks by 80%, but a multiyear deployment would cost about \$27/ha/yr, requiring weekly inspection and maintenance. In either case, the resources and effort required would require justification by a motivated community. Sociocultural analyses need to be done to understand what would be required to get a community to act with commitment. At the time, the inflammatory comment 'one might easily imagine the scenario were *I. dammini* found to transmit a lethal agent such as tick borne encephalitis virus' (Telford 1993) was a contemplation of what it would take to get communities to act; the scenario should now be entertained given the emergence of deer tick virus (which had not yet been identified) as a public health threat (El Khoury et al. 2013). Clearly, in some places, deer reduction may not be economically or sociopolitically feasible or the effort required to do so effectively would suggest that other modes in our integrated tick management toolbox might be better options. Local difficulty in implementing deer reduction does not diminish its potential utility elsewhere.

The actual effect of deer reduction needs to be better conceptualized in terms of landscape ecology. I suggest that a model in which deer are less dense, risk is present only in circumscribed sites where deer aggregate (functional refugia, McCullough 1987; core area, Kilpatrick et al. 2001) and where the habitat structure is permissive for the tick (Wilson et al. 1990). As deer herds become more dense, additional food is sought outside of the core area and deer transport fed female ticks farther; the foci coalesce and even marginal habitats for the tick may become infested due to overall greater tick reproductive success (Fig. 1). The reverse scenario should be expected for deer reduction: foci become less coalesced, shrinking to the original core areas as deer become less dense (Kilpatrick et al. 2001), and areas that are more marginal with respect to tick habitat structure become free of ticks. Eventually, risky foci are found to be dispersed as opposed to more generally distributed and human encounters with ticks less probable. Such a landscape is likely to characterize many suburban areas, containing foci of risk interspersed with marginal habitat. These foci coalesce as deer density increases, thereby increasing the probability of more uniformly distributed dense tick infestations and human encounters with ticks.

The public health impact of deer reduction requires further study; there simply is insufficient data to conclude that deer reduction will not reduce Lyme disease risk. Few of the published studies actually demonstrate that reducing deer density will reduce prevalence or incidence of Lyme disease (Garnett et al. 2011, Kugeler et al. 2016) but there are three (Great Island, Bluff Point, Monhegan; Telford 1993, Rand et al. 2004, Kilpatrick et al. 2014) that provide data on human incidence and all three demonstrate reduced risk after deer reduction. The evidence for an effect on incidence has been criticized for these studies (Kugeler et al. 2016) based upon the lack of defined or standardized human Lyme disease case definitions. Bluff Point experienced an accelerated reduction in reported cases relative to what might be expected from the 2 yr deer tick life cycle, leading to the suggestion that the cause for any decline in reported cases for any of these studies was likely multifactorial and not due to deer reduction alone. (It might be argued, however, that even if other factors such as community awareness operated to help reduce incidence during a deer reduction experiment, nonetheless any reduction in reported cases is a good thing and consistent with the perspective of an integrated tick management program.) In contrast, one study (Jordan et al. 2007) does not demonstrate an effect on incidence but used cases reported from a wider area than where deer reduction was implemented. The studies published to date were not designed for robust epidemiological evaluations and should not be considered the final word.

It should be noted that the only intervention that has ever been conclusively demonstrated to reduce the risk of Lyme disease at the community level is vaccination. The Phase III trials for Lymerix (Steere et al. 1998) reduced incidence by 60–80% as did that for another human Lyme disease vaccine (Sigal et al. 1998). A main reason for deer reduction or any other mode of intervention against Lyme disease (e.g., use of repellents, application of granular insecticide, permethrin-treated clothing) not having demonstrated a reduction of actual risk is because prospective human subjects studies are difficult and expensive. For example, the Lymerix clinical trial assumed an attack rate of 0.5% and required treatment and comparison arms of 4000 subjects apiece to ensure that the lower bound of the efficacy confidence interval exceeded 60% (80% power). The amount of money required for this trial (late 1990s) was more than $25 million dollars. Experiments of deer reduction or other nonpharmaceutical modes of intervention have not had the magnitude of funding required to undertake concurrent definitive prospective epidemiological studies. Accordingly, the surrogate for documenting risk reduction as a result of an environmental intervention has been documenting a reduction in the density of deer ticks, sometimes complemented with estimates of prevalence of infection in host seeking ticks.

Deer reduction as a mode of intervention against Lyme disease and the other infections transmitted by deer ticks in the eastern United States has been hindered by misunderstandings about its goals. Definitive human prospective studies to evaluate the effects of deer reduction on risk may be unlikely to be done because the funding that is required would not be made available to allow for the sample sizes that are required. It is wrong to conclude that deer

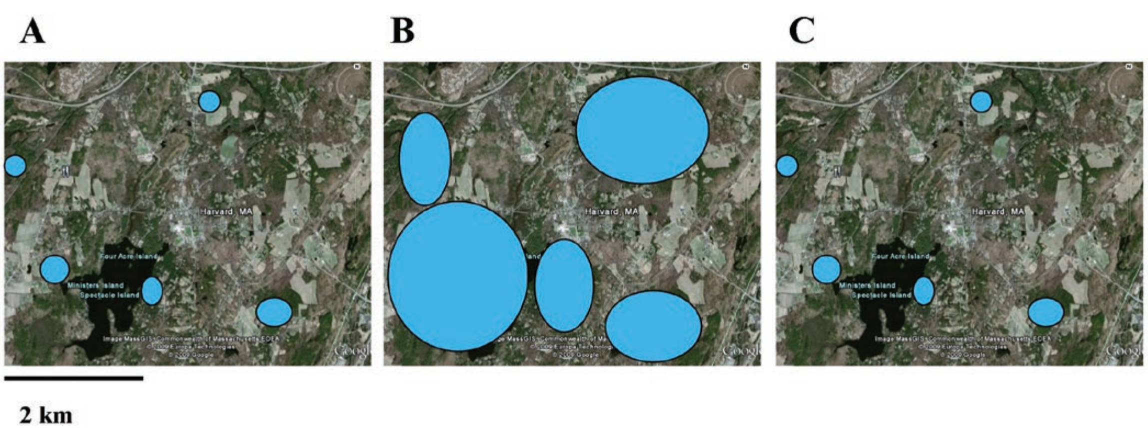

Fig. 1. Representation of the risk landscape before and after deer reduction. (A) Prior to major zoonotic risk: small isolated natural foci within core areas of deer home range; (B) Expansion and coalescence of multiple natural foci as deer herds become dense; public health is burdened; (C) reduction of the risk landscape as a result of local deer reduction within coalesced foci; reduction of zoonotic risk. Maps modified from GoogleMaps.

reduction does not reduce risk based on the published acarological studies, a less than complete surrogate for human exposure studies. Indeed, such a conclusion is based on absence of evidence, not evidence of absence of an effect and harms future attempts to use deer reduction as part of an integrated tick management system.

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