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Evidence for Personal Protective Measures to Reduce Human Contact With Blacklegged Ticks and for Environmentally Based Control Methods to Suppress Host-Seeking Blacklegged Ticks and Reduce Infection with Lyme Disease Spirochetes in Tick Vectors and Rodent Reservoirs

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Abstract

In the 1980s, the blacklegged tick, *Ixodes scapularis* Say, and rodents were recognized as the principal vector and reservoir hosts of the Lyme disease spirochete *Borrelia burgdorferi* in the eastern United States, and deer were incriminated as principal hosts for *I. scapularis* adults. These realizations led to pioneering studies aiming to reduce the risk for transmission of *B. burgdorferi* to humans by attacking host-seeking ticks with acaricides, interrupting the enzootic transmission cycle by killing immatures infesting rodent reservoirs by means of acaricide-treated nesting material, or reducing deer abundance to suppress tick numbers. We review the progress over the past three decades in the fields of: 1) prevention of human–tick contact with repellents and permethrin-treated clothing, and 2) suppression of *I. scapularis* and disruption of enzootic *B. burgdorferi* transmission with environmentally based control methods. Personal protective measures include synthetic and natural product-based repellents that can be applied to skin and clothing, permethrin sprays for clothing and gear, and permethrin-treated clothing. A wide variety of approaches and products to suppress *I. scapularis* or disrupt enzootic *B. burgdorferi* transmission have emerged and been evaluated in field trials. Application of synthetic chemical acaricides is a robust method to suppress host-seeking *I. scapularis* ticks within a treated area for at least 6–8 wk. Natural product-based acaricides or entomopathogenic fungi have emerged as alternatives to kill host-seeking ticks for homeowners who are unwilling to use synthetic chemical acaricides. However, as compared with synthetic chemical acaricides, these approaches appear less robust in terms of both their killing efficacy and persistence. Use of rodent-targeted topical acaricides represents an alternative for homeowners opposed to open distribution of acaricides to the ground and vegetation on their properties. This host-targeted approach also provides the benefit of the intervention impacting the entire rodent home range. Rodent-targeted oral vaccines against *B. burgdorferi* and a rodent-targeted antibiotic bait have been evaluated in laboratory and field trials but are not yet commercially available. Targeting of deer—via deer reduction or

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treatment of deer with topical acaricides—can provide area-wide suppression of host-seeking *I. scapularis*. These two deer-targeted approaches combine great potential for protection that impacts the entire landscape with severe problems relating to public acceptance or implementation logistics. Integrated use of two or more methods has unfortunately been evaluated in very few published studies, but additional field evaluations of integrated tick and pathogen strategies are underway.

Keywords

Borrelia burgdorferi; *Ixodes scapularis*; blacklegged tick; Lyme disease; risk management

In the early 1980s, the blacklegged tick, *Ixodes scapularis* Say (including the junior synonym *Ixodes dammini* Spielman, Clifford, Piesman & Corwin), was implicated as a vector to humans in the eastern United States of the Lyme disease spirochete *Borrelia burgdorferi* (Burgdorfer et al. 1982; Spielman et al. 1985; Piesman et al. 1987a,b). Rodents, particularly the white-footed mouse, *Peromyscus leucopus* (Rafinesque), were recognized as primary enzootic spirochete reservoirs (Levine et al. 1985, Donahue et al. 1987, Mather et al. 1989) and the white-tailed deer, *Odocoileus virginianus* (Zimmerman), was shown to be the principal host for the adult stage of *I. scapularis* (Piesman et al. 1979, Main et al. 1981). These findings led to pioneering field studies aiming to reduce the risk for transmission of *B. burgdorferi* to humans by directly attacking host-seeking ticks with acaricide applied to the ground substrate and vegetation (Schulze et al. 1987), interrupting the enzootic transmission cycle by killing immatures infesting rodent reservoirs by means of acaricide-treated nesting material (Mather et al. 1987a), or reducing the abundance of white-tailed deer to suppress tick numbers (Wilson et al. 1988). Nearly three decades later, a wide array of approaches to avoid contact with ticks through personal protective measures, suppress host-seeking *I. scapularis*, or disrupt enzootic *B. burgdorferi* transmission through environmentally based control methods have emerged.

We review the evidence for personal protective measures to reduce human contact with *I. scapularis* and for environmentally based control methods to suppress host-seeking nymphs and *B. burgdorferi* infection in nymphs and rodent reservoirs. Published literature was queried by searching the Scopus database, last done in December 2015. The search spanned the years 1960 to present and used the following key words: 1) "*Ixodes scapularis*" and 2) "*Ixodes dammini*". Additional searches using the same key words were conducted in PubMed and the Armed Forces Pest Management Board's Literature Retrieval System. The snowball technique, which identifies additional publications based on referenced materials, was then employed to identify additional publications of interest. Because most human infections with *B. burgdorferi* in the eastern United States are considered to result from bites by infected *I. scapularis* nymphs (Spielman et al. 1985; Piesman 1987a; Falco et al. 1996, 1999; Mead 2015), we focus primarily on the impact of personal protective measures against nymphal tick bites, and the impact of environmentally based interventions on the abundance of host-seeking nymphs, infection rates of host-seeking nymphs with *B. burgdorferi*, and the abundance of infected nymphs. As used in this paper, data for abundance or density of host-seeking ticks (e.g., <0.1 nymphs/100 m^2) generated by drag or flag sampling should be interpreted as relative abundance and relative density rather than as absolute estimates of the nymphal population present. Prospects for current personal protective measures and environmentally based tick and pathogen suppression methods to reduce Lyme disease will be discussed in a separate forthcoming paper.

Protection Against Bites by *I. scapularis* With Spray-On Repellents

Laboratory assays with *I. scapularis* have demonstrated repellency for synthetic chemical compounds (e.g., deet, EBAAP [IR3535], icaridin [also known as picaridin], AI3-37220, and SS220) as well as natural product compounds in the form of plant essential oils or their components (e.g., amyris essential oil, callicarpenal, carvacrol, Chinese juniper essential oil, Chinese weeping cedar essential oil, common juniper essential oil, elemol, geraniol, intermedeol, isolongifolenone, nootkatone, and 2-undecanone from wild tomato plants; Carroll et al. 1989, 2004, 2005, 2007, 2010, 2011; Dietrich et al. 2006; Carroll 2008; Bissinger et al. 2009, 2014; Feaster et al. 2009; Zhang et al. 2009; Dolan and Panella 2011; Büchel et al. 2015). Several of these compounds can be applied to skin and clothing and have been evaluated for repellent efficacy against *I. scapularis* in the field (Table 1).

In trials with treated military clothing, deet provided >80% protection against contact with *I. scapularis* ticks recovered crawling on clothing or skin or found attached to test subjects (Schreck et al. 1986, Evans et al. 1990; Table 1). High levels of repellency were also recorded for textiles—tick drag cloths or coveralls worn in the field—treated with natural product-based compounds, including nootkatone (100% repellency for up to 3 d after application), carvacrol (>90% repellency for up to 2 d), and combinations of essential oils including rosemary and geraniol oils (>90% repellency for up to 3 d; Schulze et al. 2011, Jordan et al. 2012; Table 1). Published data for the ability of repellents applied to human skin to protect against tick bites—in trials where attached ticks are recovered and identified—are unfortunately lacking for *I. scapularis* but data for *Ixodes ricinus* (L.) in Europe suggest that protection is in the range of 40–65% for deet and lemon eucalyptus extract (Staub et al. 2002, Gardulf et al. 2004). Research is needed to clarify the protective effect against bites by *I. scapularis* nymphs of repellents applied to human skin and typical summer clothing.

Protection Against Bites by *I. scapularis* With Permethrin-Treated Clothing

Permethrin, which is labeled for use as a clothing treatment and should not be applied directly to skin, functions primarily as a contact toxicant with limited spatial repellency for ixodid ticks (Schreck et al. 1982, Lane and Anderson 1984, Lane 1989, Faulde et al. 2003). Trials with people wearing permethrin-treated military clothing or coveralls while moving around in tick habitat have demonstrated high levels (>95%) of protection against *I. scapularis* found crawling on or attached to subjects wearing treated clothing (Schreck et al. 1986, Evans et al. 1990, Jordan et al. 2012; Table 1). Miller et al. (2011) determined the protective effectiveness of permethrin-treated summer weight-clothing, including shoes, socks, shorts, and t-shirts, against challenges by *I. scapularis* nymphs introduced onto various parts of the body (shoes versus legs or arms) of human volunteers. The reduction in the number of nymphs that attached to volunteers with permethrin-treated clothing, as compared with similar but nontreated clothing, was >95% when nymphs were introduced onto shoes but far lower when they were introduced onto legs just above the knee (56–69%) or arms just above the elbow (12–47%). The majority (77%) of attached nymphs died within hours of their attachment on volunteers with permethrin-treated clothing whereas nearly all nymphs attaching to volunteers with nontreated clothing remained alive. Moderate to high levels of protection for field use of permethrin-treated clothing were also reported for *Ixodes pacificus* Cooley & Kohls in the far western United States, *I. ricinus* in Europe, and the lone star tick, *Amblyomma americanum* (L.) (Schreck et al. 1980, 1982; Lane 1989; Faulde et al. 2008, 2015; Vaughn and Meshnick 2011; Richards et al. 2014; Vaughn et al. 2014). Research is needed to clarify the protective effect against bites by *I. scapularis* nymphs of typical summer clothing treated with permethrin and worn during normal daily activities.

Suppression of *I. scapularis* and *B. burgdorferi* With a Single Environmentally Based Control Method

In this section, we review studies that evaluated a single environmentally based tick and pathogen management intervention within the following general approaches: landscape or vegetation management (Table 2); targeting of host-seeking ticks with synthetic or natural product-based chemical acaricides or biological agents (Tables 3–5); rodent reservoir-targeted topical acaricides or oral antibiotic or vaccine baits (Tables 6–7); and deer-targeted strategies including deer reduction, deer exclusion, or deer-targeted acaricides (Tables 8–10). Data presented in these tables are restricted to outcomes for *I. scapularis* nymphs, whereas the text also briefly addresses studies with outcomes for adults. Because homeowner-driven interventions aim to suppress *I. scapularis* and *B. burgdorferi* on residential properties, it is important to assess the effectiveness of an intervention specifically on residential properties. While it may be advantageous to determine efficacy of a given intervention in woodland settings, due to uniform vegetation composition and high abundance of both ticks and small mammal reservoirs, intervention effectiveness may differ among woodlands and residential properties due to variation in microclimate, ground substrate or vegetation, adequate host-seeking tick populations, and small mammal reservoir composition. We therefore differentiate between studies conducted in residential versus woodland settings.

Benefits and drawbacks of collecting host-seeking ticks by dragging versus flagging or walking, and collection considerations relating to daily weather conditions and time-of-day, were discussed previously (Ginsberg and Ewing 1989; Schulze et al. 1997, 2001a; Schulze and Jordan 2003; Eisen and Eisen 2016). Some studies have used infestation of *I. scapularis* nymphs on rodents to assess the effect of an intervention. Although collection of host-seeking nymphs has its own set of challenges, it likely is more representative of human risk of encountering nymphs as compared with infestation by nymphs on rodents. Another consideration is whether to use removal or nonremoval sampling techniques to assess the outcome of an intervention. A benefit of nonremoval sampling is that the study outcome is not impacted by ticks being removed, which may impact the results in test areas with low tick abundance and numerous repeated sampling occasions. Removal sampling can provide more accurate morphological tick species identification in the laboratory and cannot be avoided when there is a need to determine the prevalence of infection with *B. burgdorferi* in collected nymphs.

Depending on whether or not preintervention data are collected, there are two basic approaches to estimate percent reduction when determining outcome measures resulting from a field intervention. In the absence of preintervention data, the postintervention treatment value (Y) and postintervention control value (X) are used as described by Abbott (1925) to estimate percent reduction attributable to the treatment: percent control = ((X − Y)/X) × 100. When both pre- and postintervention data are generated, percent control can be estimated to account for pre- and posttreatment time points in both control and treatment areas, as described by Henderson and Tilton (1955) or Mount et al. (1976). Mount et al. (1976) gives the following formula to calculate percent control obtained with an acaricide in treatment areas (T) as compared with untreated control areas (U): percent control = 100 − ((T/U) × 100), where T = (posttreatment mean/pretreatment mean) in treated areas and U = (posttreatment mean/pretreatment mean) in untreated control areas. To account for additional factors in the assessment of percent reduction resulting from the intervention, new statistical options are emerging which include generalized mixed linear models.

Landscape or Vegetation Management to Reduce Tick Habitat and Physical Barriers to Prevent Movement of Host-Seeking Ticks

Stafford (2007) gives a comprehensive general overview of landscape and vegetation management methods with potential to reduce the risk of exposure to host-seeking ticks. However, field evaluations of the effectiveness of landscape or vegetation management to suppress *I. scapularis* nymphs are scarce (Table 2). Removal of leaf litter with hand rakes and leaf blowers in wooded areas of a forested residential community in New Jersey reduced the abundance of host-seeking *I. scapularis* nymphs by 75–77% (Schulze et al. 1995). Burning of woodland vegetation has produced variable results for reduction (ranging from 50–97%) of host-seeking *I. scapularis* nymphs in subsequent months (Mather et al. 1993, Stafford et al. 1988). Not surprisingly, intense burns result in stronger reduction in nymphal abundance. However, Mather et al. (1993) found that the reduction in nymphal abundance in burn sites was counteracted by higher prevalence of *B. burgdorferi* infection in nymphs within the same sites as compared to a control site, resulting in similar abundance of infected nymphs in both burn and control sites.

Other landscape-based field intervention trials have focused on the adult stage of *I. scapularis* in nonresidential settings. Silt fence barriers, made from polypropylene plastic fabric, were shown to reduce the abundance of *I. scapularis* adults, but not nymphs, in pastures (Carroll and Schmidtmann 1996). Two woodland studies in Connecticut showed that removal of the invasive Japanese barberry (*Berberis thunbergii* de Candolle) shrub, which previously was found to be associated with elevated abundance of host-seeking *I. scapularis* in Maine (Lubelczyk et al. 2004, Elias et al. 2006), could substantially reduce the abundance of host-seeking *I. scapularis* adults as well as *B. burgdorferi*-infected adults (Williams et al. 2009, Williams and Ward 2010). Other studies have demonstrated strong negative impacts of burning or mowing on the abundance of host-seeking *I. scapularis* adults (Rogers 1953, Wilson 1986, Gleim et al. 2014).

Maupin et al. (1991) reported that host-seeking *I. scapularis* nymphs are most numerous in wooded areas directly adjacent to residential properties (accounting for 67% of collected nymphal ticks), followed by the unmaintained woods and lawn edge or ecotone (22%), ornamental vegetation (9%), and lawns (2%). Stafford and Magnarelli (1993) presented similar results, with host-seeking *I. scapularis* nymphs collected more commonly in woodland and woodland ecotone (accounting for 78% of collected nymphs) than on lawns or in grassy ecotones. Moreover, a majority of nymphs recovered from lawns were <2 m from the woods and lawn edge (Carroll et al. 1992, Stafford and Magnarelli 1993). Recognition of the woods and lawn edge as a primary tick exposure risk microhabitat on residential properties led to the recommendation of establishing a >1-m-wide artificial border between the woods and lawn consisting of xeric materials (e.g., gravel or wood chips) to minimize migration of host-seeking ticks from the woods and lawn edge into portions of the property with more intense human use (Maupin et al. 1991, Hayes and Piesman 2003, Schulze and Jordan 2006, Stafford 2007). Patrican and Allan (1995a) reported moderate reduction in movement by *I. scapularis* nymphs across crushed stone (30% reduction) but not across pine-bark woodchips in a laboratory bioassay.

Piesman (2006) further examined the response of *I. scapularis* nymphs to various types of potential barrier materials, including forest products, sand, soil, and gravel, in the laboratory. Only a few materials impeded nymphal movement, including sawdust and wood chips from Alaska yellow cedar, *Chamaecyparis nootkatensis* (D. Don), and cellulose. Both Alaska yellow cedar woodchips and cellulose lost their potential to impede nymphal movement within a week of outdoor exposure, whereas Alaska yellow cedar sawdust remained effective up to 4 wk after outdoor exposure. Field studies are still lacking to quantify the protective efficacy of barrier treatments, including different barrier materials, placement, and widths.

Perhaps more than for any other promising tick-bite prevention approach, data-based evaluations are lacking for the capacity of landscape and vegetation manipulation to reduce human contact with host-seeking *I. scapularis* nymphs in residential settings and high-use recreational areas. Research is urgently needed to prove or disprove the intuitive notion that landscape and vegetation manipulation can be an effective method to reduce human bites by *I. scapularis* nymphs.

Application of Synthetic Chemical Acaricides to Ground Substrate and Vegetation

Field studies on the effectiveness of synthetic chemical pesticides to suppress host-seeking *I. scapularis* were initiated in the late 1980s. To date they have included two organophosphate pesticides that are no longer available for residential tick control (chlorpyrifos and diazinon), three pyrethroid pesticides (bifenthrin, cyfluthrin, and deltamethrin), and one carbamate pesticide (carbaryl; Table 3). These pesticides are labeled for and can be applied to ground substrate and vegetation as granules or as sprays broadcast with low-pressure, low-volume or high-pressure, high volume sprayers. Application restrictions for these chemical acaricides include that they cannot be applied to ground substrate or vegetation near open water, wetlands, wellheads, or plants meant for human consumption.

Even during tick activity periods, only a small portion of the total population of *I. scapularis* nymphs may, at any given time, be positioned as to be readily contacted by a low-pressure spray acaricide application, with the other nymphs located in microhabitats not easily reached by the low-pressure spray application, such as within the soil and leaf litter layer (Eisen and Eisen 2016). Consequently, a low-pressure spray application with a nonpersistent acaricide can have a strong immediate suppressive effect but very limited impact on the abundance of host-seeking nymphs within a few days to weeks after the application. This is most likely due to the fact that nymphs that were protected during the spray event are less likely to encounter viable pesticide when they later leave their protected microhabitats to seek hosts. Conversely, a high-pressure spray application with a persistent acaricide maximizes the likelihood that a majority of the total nymphal population will be contacted by the acaricide, either during the spray event or as they move from protected microhabitats to assume favorable host-seeking positions. One intriguing but not yet fully realized solution to increase the likelihood of contact between *I. scapularis* and an acaricide applied to the ground substrate and vegetation is to apply a formulation where the acaricide is combined with an arrestment pheromone (Sonenshine et al. 2003). Another factor to consider is the impact of weather, particularly rainfall, on spray or granular acaricide applications. Rainfall has been suggested to be beneficial, as it may drive an already applied acaricide deeper into the ground substrate, thus potentially contacting a greater portion of the total population of nymphs. On the other hand, rainfall run-off may remove acaricide from the treated area. Research is needed to clarify the impact of rainfall following application of various types of acaricides.

A seminal study in New Jersey woodlands demonstrated ≥97% reduction in the abundance of host-seeking seeking *I. scapularis* adults 3 d after high-pressure spray application of formulations containing carbaryl or diazinon (Schulze et al. 1987). This was followed by a series of studies in New Jersey demonstrating reduced infestation by *I. scapularis* immatures on white-footed mice after granular application of carbaryl (62–100% control depending amount of carbaryl applied per ha), diazinon (54%), and chlorpyrifos (81%); and 94% reduction in host-seeking adults 4 d after aerial spray application of carbaryl (Schulze et al. 1991, 1992, 1994). Moreover, a laboratory study demonstrated that *I. scapularis* immatures were susceptible to carbaryl and three pyrethroids: cyfluthrin, esfenvalerate, and permethrin (Maupin and Piesman 1994). Of these, cyfluthrin and permethrin were more toxic to nymphs than carbaryl.

In the early 1990s, the focus shifted to evaluating the impact of synthetic chemical acaricides on host-seeking *I. scapularis* nymphs once this life stage was identified as the principal vector of *B. burgdorferi* to humans. Peak nymphal activity periods span roughly 2–3 mo in the spring and early summer in the Northeast (Stafford 2007), indicating an intervention should ideally provide sustained control for at least 8 wk. As summarized in Table 3, synthetic chemical acaricides, particularly pyrethroids, can provide sustained suppression of host-seeking nymphs for at least 6 wk based on a single granular or spray application (Stafford 1991a; Solberg et al. 1992; Curran et al. 1993; Allan and Patrican 1995; Schulze and Jordan 1995; Schulze et al. 2000, 2001b, 2005, 2008a; Rand et al. 2010; Stafford and Allan 2010, Elias et al. 2013). Key findings from individual studies are described below and are arranged by type of acaricide.

Organophosphates—Application of chlorpyrifos (0.6–1.1 kg active ingredient [AI]/ha) resulted in ≥84% reduction in abundance of host-seeking *I. scapularis* nymphs up to 6 wk regardless of whether it was distributed via low- or high-pressure spray or as granules (Allan and Patrican 1995, Curran et al. 1993). At the highest application rate (1.1 kg AI/ha), there was a ≥90% reduction for up to 6 wk in residential settings (Curran et al. 1993). In residential landscapes, application of organophosphates uniformly reduced the abundance of host-seeking nymphs to <0.1/100 m^2 for 6 wk (Table 3).

Carbamates—Stafford (1991a) reported that a single high-pressure spray application of carbaryl (1.5–2.1 kg AI/ha) made in June consistently suppressed host-seeking *I. scapularis* nymphs by >90% over a 7–8-wk period in a residential area in Connecticut. Single high-pressure spray applications using lower amounts of carbaryl (0.6–1.1 kg AI/ha) in a residential area in New York resulted in less effective control with 64–87% suppression of nymphs after 2–6 wk (Curran et al. 1993). Application of granular carbaryl (4.5 kg AI/ha) in the same residential setting produced 89% reduction in abundance of host-seeking nymphs after 1 wk but declined to 70–71% after 4–6 wk (Curran et al. 1993). Schulze et al. (2000) reported a similar level of control (73%) 1–5 wk after application of granular carbaryl (4.5 kg AI/ha) in a New Jersey woodland. Application of granular carbaryl (4.5 kg AI/ha) in plots with variable leaf litter depth resulted in similar levels of suppression of host-seeking *I. scapularis* nymphs within the first week of application (91–96% control), whereas suppression was much higher in plots with sparse, as compared with deeper, leaf litter after 7–8 wk (87 and 47% control, respectively; Schulze and Jordan 1995). In residential settings, application of carbamate pesticide uniformly reduced the abundance of host-seeking nymphs to <0.35/100 m^2 up to 6 wk (Table 3).

Pyrethroids—Highly controlled experimental spring applications of pyrethroids (bifenthrin, cyfluthrin, or deltamethrin; applied at 90–410 g AI/ha) have resulted in >85% control of host-seeking *I. scapularis* nymphal ticks up to 7 wk regardless of application method, spray pressure, or woodland versus residential setting (Solberg et al. 1992; Curran et al. 1993; Schulze et al. 2001b, 2005; Rand et al. 2010; Stafford and Allan 2010; Elias et al. 2013; Table 3). Moreover, a ≥95% reduction of host-seeking nymphs was recorded from all but two of these studies (Table 3). In contrast, a large-scale, effectiveness study, of bifenthrin applied by commercial companies resulted in 69% control of *I. scapularis* nymphs on treated properties in one of two evaluation years and 45% in the other year (Hinckley et al. 2016; Table 3). Levels of control typically achieved when an individual homeowner engages a commercial pest control company, and the reasons for decreased efficacy as compared with optimal experimental applications, merit further study.

Studies performed in residential landscapes demonstrate that highly controlled application of pyrethroid pesticides near uniformly reduces the abundance of host-seeking nymphs to ≤0.3/100 m^2 up to 6 wk (Table 3). In addition, fall applications of pyrethroids demonstrated substantial suppression of host-seeking nymphs >6 mo later when treatment areas were sampled the following spring (Solberg et al. 1992, Schulze et al. 2008a; Table 3).

Application of Natural Product-Based Acaricides to Ground Substrate and Vegetation

Because some homeowners are reluctant to use synthetic chemical acaricides on their properties (Gould et al. 2008), research was initiated to find natural product-based alternative chemical compounds. Early studies for controlling *I. scapularis* with natural products focused on pyrethrin (pyrethrum), a natural insecticidal compound derived from *Chrysanthemum* spp. (Table 4). Laboratory bioassays using various all-natural substrates demonstrated high (78–100%) killing efficacy of a pyrethrin-based soap for *I. scapularis* nymphs, similar to that of chlorpyrifos (88–95%; Allan and Patrican 1994, Patrican and Allan 1995a). Subsequent field trials in New York woodlands with pyrethrin-based soap provided >90% reduction of host-seeking *I. scapularis* nymphs 1 wk after treatment (Allan and Patrican 1995, Patrican and Allan 1995b). However, percentage control fell to 60–66% after 2 wk and <25% after 3–6 wk as compared with >90% reduction across all time points for chlorpyrifos. This finding is consistent with the nonpersistent nature of pyrethrin, which breaks down readily following exposure to light and oxygen.

Laboratory studies have explored the potential of a wide variety of plant-based compounds to kill *I. scapularis*, including compounds derived from various species of cedar, other coniferous trees, shrubs, and herbs (Panella et al. 1997, 2005; Dolan et al. 2007; Flor-Weiler et al. 2011; Eller et al. 2014). Many of these compounds demonstrated effective killing activity against nymphal ticks. Extracts from heartwood of cedar are among the most potent (Panella et al. 1997, Dolan et al. 2007). Panella et al. (2005) examined 15 natural products isolated from essential oil components extracted from Alaska yellow cedar heartwood. Of these, strong killing activity against *I. scapularis* nymphs for up to 6 wk was recorded for nootkatone. Nootkatone is found not only in Alaska yellow cedar but also in other natural sources, including many citrus products and grapefruit. Flor-Weiler et al. (2011) later demonstrated that nootkatone from essential oil of grapefruit effectively kills nymphs of *I. scapularis* and other important human-biting ticks in the United States. They also report that nootkatone volatilizes rapidly and thus may be nonpersistent in the field. This finding led to the development of a novel lignin-encapsulated nootkatone formulation that is less volatile, less sensitive to sunlight, and less phytotoxic to plants while at the same time more toxic to *I. scapularis* nymphs in laboratory bioassays (Behle et al. 2011). However, a field trial demonstrated >90% loss of lignin-encapsulated nootkatone from leaf litter and soil substrates 1 wk after application (Bharadwaj et al. 2012)

In addition to the previously mentioned studies with pyrethrin, field evaluations have focused primarily on nootkatone but also included carvacrol (an essential oil component that occurs in heartwood of Alaska yellow cedar as well as various herbs, including oregano), garlic oil, and combinations of essential plant oils including rosemary, peppermint, and wintergreen. Results from these field evaluations are mixed (Table 4). Initial single applications of a nootkatone formulation with a low-pressure sprayer in New Jersey woodlands provided >75% reduction in host-seeking *I. scapularis* nymphs through 2 wk but only 41–50% reduction by 4 wk (Dolan et al. 2009). In the same set of experiments, application of a carvacrol formulation resulted in >75% reduction in host-seeking *I. scapularis* nymphs up to 4 wk.

Follow-up experiments to compare low- and high-pressure spray applications of a 2% nootkatone formulation revealed that reduction in host-seeking *I. scapularis* nymphs fell from 82–84% by 1–2 wk after application to 40–61% by 4–5 wk for a single low-pressure spray application, whereas a single high-pressure spray application resulted in >98% reduction in host-seeking nymphs up to 6 wk after application (Dolan et al. 2009). High-pressure spraying should provide greater penetration into the vegetation and ground substrate and therefore reach a higher proportion of the nymphal population before the natural product-based active ingredient starts to break down and killing efficacy is lost. Use of a “nanoemulsion” where corn oil was added to a nootkatone formulation reduced nymphal abundance by 85% at the 4 wk time point even when applied with a low-pressure backpack sprayer (Dolan et al. 2009). This finding underscores the importance of formulating nootkatone, and most likely other natural product-based compounds, in a manner that extends the period during which they effectively kill ticks in the field. However, a subsequent study by Bharadwaj et al. (2012) in a residential setting in Connecticut produced contradictory results. First, a single high-pressure spray application with a nootkatone formulation failed to reduce host-seeking *I. scapularis* nymphs beyond 2 wk. Second, use of the previously mentioned novel formulation with lignin-encapsulated nootkatone resulted in 100% reduction in host-seeking *I. scapularis* nymphs over a 4-wk period in one year but only 13–50% reduction after 2–4 wk in the following year. The reason for this dramatic difference is not clear, but may have been related to weather conditions. In residential settings, high-pressure spray application of nootkatone or encapsulated nootkatone uniformly reduced the abundance of host-seeking nymphs to <1.5/100 m^2 up to 2 wk and to <4.5/100 m^2 up to 4 wk (Table 4).

Homeowners are typically limited to low-pressure hand-held and back-pack type sprayers for application of over-the-counter acaricides without the involvement of a licensed pesticide applicator. Jordan et al. (2011) examined if two well-timed backpack sprayer applications, spaced 2 wk apart, of a nootkatone formulation could provide prolonged, substantial tick reduction. Such dual application resulted in sustained >80% reduction in host-seeking *I. scapularis* nymphs over a 6-wk period, with all but one weekly samples showing >90% control. In the same experimental scenario with dual low-pressure spray applications 2 wk apart, use of a carvacrol formulation resulted in sustained >75% control over 6 wk, with most weeks having >85% control, whereas use of a product with rosemary oil as the primary active ingredient showed >70% control over 4 wk but then fell to 67 and 30%, respectively, after 5 and 6 wk (Jordan et al. 2011). For another rosemary oil-based product, a single high pressure spray application resulted in 100% reduction of host-seeking *I. scapularis* nymphs up to 2–4 wk after application in Maine woodlands (Rand et al. 2010, Elias et al. 2013). Most recently, a single high pressure spray application of a garlic oil-based product was shown to result in 37–59% control 1–3 wk after application (Bharadwaj et al. 2015).

Data shown in Table 4 reveal a general pattern for natural product-based acaricides where single low-pressure spray applications provide substantial control of *I. scapularis* nymphs for 1–3 wk. Control of ticks beyond 3 wk can be achieved by either single high-pressure spray applications or multiple low-pressure spray applications. Moreover, natural product-based acaricides do appear to be more sensitive to environmental conditions as compared with synthetic chemical acaricides. The outcome of treating a residential property with a natural product-based acaricide therefore is more uncertain than for a traditional synthetic acaricide. Efforts to improve formulations of natural product-based acaricides in order to increase persistence and reduce phytotoxicity are warranted. Additional research regarding the impact of weather related events and the timing of application on the efficacy of natural product-based acaricides for controlling *I. scapularis* nymphs is needed.

Robotic Device for Collection and Killing of Host-Seeking Ticks With an Acaricide

Although not yet evaluated for use against *I. scapularis*, a four-wheeled robotic device (TickBot) for collection and killing of host-seeking ticks described by Gaff et al. (2015) is worth mentioning. The device is fitted with a permethrin-treated cloth and travels along a guide wire. The guide wire could be placed along a trail edge or in the ecotone within a residential property. Initial trials demonstrated the TickBot to suppress *A. americanum* ticks for up to 24 h. Additional research is needed to refine and define applicability of robotic devices for tick control.

Dusting With Desiccants or Pyrethrin-Augmented Desiccants

Desiccants have been shown to disrupt the exoskeleton through mechanical, cutting action and may lead to desiccation of exposed ticks. Some desiccant dusts contain only silica-based ingredients that act mechanically (e.g., diatomaceous earth), whereas others are augmented with pyrethrin and the synergist piperonyl butoxide (e.g., Drione; Bayer Environmental Science, Research Triangle, NC). Laboratory studies evaluating various natural substrates resulted in <20% killing efficacy of diatomaceous earth against *I. scapularis* nymphs, whereas Drione provided 83–99% mortality in nymphs, similar to that for pyrethrin soap (78–100%) and chlorpyrifos (88–95%; Allan and Patrican 1994, Patrican and Allan 1995a). Killing by Drione therefore likely was caused primarily by pyrethrin or piperonyl butoxide rather than silica. Mechanically acting desiccants that are not augmented by chemical acaricides appear to have very limited potential for tick control. Field trials in New York showed >78% reduction in host-seeking nymphs 1–2 wk after Drione treatment but <30% control after 3–6 wk (Allan and Patrican 1995, Patrican and Allan 1995b; Table 4). This is similar to the results outlined previously for pyrethrin soap (Table 4).

Application of Biological Control Agents to Ground Substrate and Vegetation

Similar to natural product-based chemical agents, entomopathogenic bacteria, fungi, or nematodes that serve as biological control agents may provide alternatives to application of traditional synthetic chemical acaricides. Entomopathogenic nematodes of the genera *Heterorhabditis* and *Steinernema* were found to be pathogenic to fed female *I. scapularis* but not to unfed females or fed or unfed immatures (Zhioua et al. 1995, Hill 1998). The entomopathogenic bacterium *Bacillus thuringiensis* variety *kurstaki* was shown to kill fed *I. scapularis* larvae (Zhioua et al. 1999a) but has not been tested against host-seeking ticks.

Entomopathogenic fungi appear to hold more promise for use as a control agent against host-seeking *I. scapularis*. Numerous species of entomopathogenic fungi have been isolated from soils and *I. scapularis* in the Northeast (Ginsberg and LeBrun 1996, Zhioua et al. 1999b, Benoit et al. 2005, Tuininga et al. 2009, Greengarten et al. 2011). Several species of fungi—including *Beauveria bassiana* (Balsamo-Crivelli) Vuillemin, *Hypocrea lixii*

Patouillard, *Metarhizium brunneum* (Petch) (including some varieties previously assigned to *Metarhizium anisopliae* (Metschnikoff) Sorokin), and *Penicillium soppii* Zalessky—were shown to cause mortality in both fed and unfed *I. scapularis* in laboratory trials (Zhioua et al. 1997; Benjamin et al. 2002; Kirkland et al. 2004; Hornbostel et al. 2004, 2005a; Greengarten et al. 2011). Recent laboratory evaluations have explored various formulations of *M. brunneum* with the aim to enhance duration of activity in the field. Bharadwaj and Stafford (2012) found *I. scapularis* to be susceptible to *M. brunneum* strain F52 regardless of whether it was formulated as an emulsifiable concentrate or a granular formulation, although the emulsifiable concentrate formulation provided more effective killing. Moreover, killing efficacy was positively associated with fungal spore concentration. Behle et al. (2013) reported effective killing of *I. scapularis* with a simple granular formulation containing microsclerotia of *M. brunneum* strain F52.

Results from field evaluations with entomopathogenic fungi are mixed (Table 5). Initial field studies using *M. brunneum* strain ESC 1 applied with a low-pressure sprayer to tick habitat reduced host-seeking *I. scapularis* by 12–26% at 4 wk after treatment for nymphs and by 36% within 1 wk after treatment for adults (Benjamin et al. 2002; Hornbostel et al. 2004, 2005a). In addition, collections of field-exposed *I. scapularis* nymphs and adults were made and these ticks were held for 3–4 wk under laboratory conditions. Mortality for nymphs and adults was <25 and ~50%, respectively. Low-pressure spray applications of *H. lixii* and *P. soppii* resulted in 26–39% mortality, attributable to the fungal treatment, for caged nymphs after 2 wk (Greengarten et al. 2011).

Other field trials evaluated the efficacy of *B. bassiana* strains ATCC 74040 and GHA, and *M. brunneum* strain F52 (Table 5). Stafford and Allan (2010) reported 74–83% reduction in host-seeking *I. scapularis* nymphs following high-pressure spray applications with the two *B. bassiana* strains, comparable to the impact of the pyrethroid bifenthrin in the same study (86% reduction). In contrast, low pressure spray applications of *B. bassiana* made the following year resulted in a 38–55% reduction of nymphal ticks. The authors speculated that the lower efficacy for *B. bassiana* in the second year may have been related to mode of application (low-pressure sprayer), mild and wet environmental conditions favoring tick survival, or a combination of these factors. As noted previously, a high-volume/high-pressure spray application may enhance penetration of the substrate and thus allow the fungal agent to reach a greater proportion of the population of host-seeking ticks as compared with a low-volume/low-pressure application.

Studies with *M. brunneum* applied with a high-pressure sprayer produced variable reductions in host-seeking nymphs based on spore concentration of the formulation. Initial trials resulted in a 56% reduction of host-seeking nymphs on lawns and 85% reduction in wooded areas 2–6 wk after application of 2.5×10^5 spores/cm^2 (Stafford and Allan 2010). Subsequent trials along the perimeters of residential properties produced reductions of 87 and 96%, respectively, 3 wk after application with 3.2×10^5 spores/cm^2 and 1.3×10^6 spores/cm^2 (Bharadwaj and Stafford 2010). Reduction in host-seeking nymphs remained >70% at 5 and 8 wk after application with the higher spore concentration, as opposed to 53% by 5 wk and 36% by 8 wk for the lower spore concentration. In residential settings, high-pressure spray application of entomopathogenic fungi uniformly reduced the abundance of host-seeking nymphs to ≤0.6/100 m^2 up to 6 wk (Table 5).

Application of entomopathogenic fungi appears to be a viable option to suppress *I. scapularis* nymphs. However, similar to natural product-based acaricides, entomopathogenic fungi appear to be more sensitive to application methodology and environmental conditions as compared with synthetic chemical acaricides. Additional research on the effect of weather and microclimate conditions, in relation to timing and mode of application and specific formulations, on the killing efficacy of entomopathogenic fungi for *I. scapularis* nymphs is warranted.

Use of Parasitoids as Biological Control Agents

A theoretically possible but most likely impractical biologically based approach to suppress *I. scapularis* is to mass-rear and release *Ixodiphagus hookeri* (Howard) (including the junior synonym *Hunterellus hookeri* Howard), a chalcid wasp parasitoid of ixodid ticks (Hu et al. 1998, Knipling and Steelman 2000). The wasp deposits eggs in fed larvae or unfed nymphs, and following their blood-meal, the nymphs are killed by the developing wasp. Natural local infestation rates of host-seeking *I. scapularis* nymphs with this parasitoid wasp in the Northeast range from 0–29% (Mather et al. 1987a, Hu et al. 1993, Hu and Hyland 1997, Stafford et al. 1996, Lyon et al. 1998). The wasp appears to be most prevalent when abundance of *I. scapularis* is high. Stafford et al. (2003) reported that the prevalence of *I. hookeri* in host-seeking *I. scapularis* nymphs decreased from 25–30% to <1% as tick abundance decreased following deer removal. Recent studies from Europe indicate that these parasitoid wasps commonly are infected with *Wolbachia* and transfer these endosymbiotic bacteria to *I. ricinus* ticks (Tijsse-Klasen et al. 2011, Plantard et al. 2012).

Rodent-Targeted Acaricides

Following the realization that the white-footed mouse is a key reservoir for *B. burgdorferi* (Levine et al. 1985, Donahue et al. 1987, Mather et al. 1989, LoGiudice et al. 2003), there has been interest in approaches that aim to reduce rodent–tick contact and thus suppress or interrupt enzootic spirochete transmission utilizing host-targeted approaches. Three basic methodologies have emerged to control ticks on rodents and other small mammal reservoirs: 1) providing the animal with acaricide-treated nesting material (e.g., Mather et al. 1987b, Hornbostel et al. 2005b); 2) host-targeted bait boxes that passively treat small mammals with an acaricide (e.g., Sonenshine and Haines 1985, Gage et al. 1997, Dolan et al. 2004, Schulze et al. 2007); and 3) providing a treated bait to achieve oral ingestion of an arthropod development inhibitor or acaricide (Slowik et al. 2001). The two former approaches have resulted in commercial products, the Damminix Tick Tube (EcoHealth Inc., Brookline, MA) with permethrin-treated cotton balls and the Select TCS bait box (formerly Maxforce TMS; Tick Box Technology Corporation, Norwalk, CT) for topical application of fipronil. Oral ingestion of a development inhibitor (fluazuron) by wood rats was found to reduce infestation by fleas but not *I. pacificus* (Slowik et al. 2001). However, this general approach merits further study with alternative compounds acting as tick development inhibitors or systemic acaricides. For example, afoxolaner and fluralaner—recently described compounds belonging to a group of systemic insecticides and acaricides termed isoxazolines (Gassel et al. 2014, Shoop et al. 2014)—were demonstrated to disrupt feeding of *I. scapularis* adults on orally treated dogs for at least 4 wk (Mitchell et al. 2014, Williams et al. 2015). Such compounds could prove useful as systemic acaricides offered via oral baits in rodent bait boxes to reduce infestation by *I. scapularis* immatures on rodent reservoirs.

Damminix Tick Tubes (hereafter referred to as Damminix) have been evaluated in multiple field studies in the Northeast yielding variable results (Table 6). The first ever field evaluation was performed by Mather et al. (1987b) in a woodland setting in Massachusetts. Damminix deployment significantly reduced *I. scapularis* immatures on white-footed mice, but the impact on host-seeking ticks was not evaluated, as the investigators did not conduct follow-up surveys of host-seeking nymphs the following spring. Notably, there was no reduction in tick infestation on voles, presumably because they did not use the treated cotton. In a subsequent study, Damminix was deployed in a residential setting in Massachusetts and resulted in near complete elimination of *I. scapularis* immatures on white-footed mice (only 1 of 40 examined mice carried immatures [3 larvae] in the treatment area, whereas 34 mice in a control area carried an average of 20 immatures; Mather et al. 1988). In the year after the Damminix deployment, reductions in key outcome measures ranged from 89% for abundance of host-seeking *I. scapularis* nymphs to 72% for prevalence of *B. burgdorferi* infection in the nymphs and 97% for the abundance of infected host-seeking nymphs (Table 6).

The dramatic reduction in abundance of infected nymphs observed by Mather et al. (1988) was, however, not uniformly evident in a set of subsequent field studies conducted in Connecticut, Massachusetts, and New York (Daniels et al. 1991; Deblinger and Rimmer 1991; Stafford 1991b, 1992; Ginsberg 1992). Deblinger and Rimmer (1991) deployed Damminix within a Massachusetts woodland setting. Infestation of white-footed mice by *I. scapularis* immatures was minimal after Damminix deployment: less than 3% of 86 examined mice carried a few immatures in the treatment area, whereas nearly 90% of mice in the control area were infested, often by >10 immatures. Moreover, the abundance of host-seeking *I. scapularis* nymphs was reduced by >95% in the treatment area in years following deployment. (Table 6). Starkly contrasting results were recorded by Daniels et al. (1991) for woodlands and residential landscapes in New York, and by Stafford (1991b, 1992) for a residential setting in Connecticut (Table 6). Although infestation of white-footed mice by *I. scapularis* immatures were reduced by the Damminix deployment in both studies, mice in treatment areas were commonly infested and average larval tick loads exceeded five per mouse during peak larval activity periods in both studies. Moreover, there was no impact on the abundance of host-seeking *I. scapularis* nymphs, or the prevalence of *B. burgdorferi* infection in the nymphs, following treatment in subsequent years for either the New York or Connecticut studies (Table 6). Finally, Ginsberg (1992) reported variable outcomes after deployment of Damminix in two different sites on Fire Island, NY. Tick burdens were greatly reduced on white-footed mice in both sites, but significant reductions in the abundance of host-seeking nymphs or their prevalence of infection with *B. burgdorferi* were not uniform across sites (Table 6). In residential settings, Damminix deployment resulted in abundance of host-seeking nymphs in the spring of the following years of 0.5–1.9/100 m^2 (or 7/h), and abundance of *B. burgdorferi*-infected host-seeking nymphs of 0.07–0.32/100 m^2 (or 0.6/h; Table 6).

One explanation for variable outcomes of Damminix deployments with regards to *B. burgdorferi*-infected host-seeking nymphs is that the reservoir contribution of white-footed mice and other rodent reservoirs that use the treated cotton varies locally. Alternative *B. burgdorferi* reservoirs that either are less likely to use cotton as nesting material or cannot access it from the tubes include voles, shrews, tree squirrels, and birds (Giardina et al. 2000, LoGiudice et al. 2003, Brisson et al. 2008). Variable impact on infestation of white-footed mice by *I. scapularis* immatures among Damminix deployment areas could result from variable mouse-to-Damminix tube ratio (with fewer individual mice accessing treated cotton when the mouse-to-tube ratio is high) or availability of other preferred naturally occurring nesting materials.

Hornbostel et al. (2005b) explored a variation of the Damminix approach by offering white-footed mice nesting material in the form of cotton treated with the entomopathogenic fungus *M. brunneum* rather than permethrin. A laboratory trial showed 75% mortality for larvae fed on mice using *M. brunneum*-treated nesting material, as compared with 35% for control mice. However, a field evaluation found no substantial impact of *M. brunneum*-treated cotton presented via nest boxes on the numbers of immatures infesting mice, or the abundance of host-seeking *I. scapularis* nymphs or the prevalence of infection with *B. burgdorferi* in the nymphs in years following treatment.

For topical application of fipronil when animals attempt to reach a food bait, there is only a single published field study on its use as a stand-alone method to suppress host-seeking infected nymphs, conducted in a residential setting in Connecticut (Dolan et al. 2004). In the laboratory, a single topical dose of 0.75% fipronil applied to mice was demonstrated to provide protection from bites by *I. scapularis* nymphs for 4–6 wk (Dolan et al. 2004). In the field, passive application of fipronil to rodents via host-targeted bait boxes reduced *I. scapularis* infestation loads on white-footed mice by 84% for larvae and 68% for nymphs (Dolan et al. 2004). Moreover, the prevalence of *B. burgdorferi*-infected mice was reduced by 53% in the treatment area, as compared with untreated areas. In the 1–2 yr after the intervention was started, reductions in key outcome measures ranged from 62–97% for abundance of host-seeking *I. scapularis* nymphs to 60% for prevalence of *B. burgdorferi* infection in the nymphs, and 85% for the abundance of infected host-seeking nymphs (Table 6). Topical application of fipronil to rodents resulted in abundance of host-seeking nymphs in the spring of the following years of 1.8–21/h, and abundance of *B. burgdorferi*-infected host-seeking nymphs of ≤1.7/h (Table 6).

Albeit simulation models are approximations of natural systems and their results should be interpreted with that caveat in mind; results from simulation modeling for use of a rodent-targeted acaricide indicate that (for per-hectare host densities of 15 white-footed mice, 10 other small mammals and birds, 1.5 medium-sized mammals, and 0.25 deer) 99% of the mice within the intervention area must be treated to reduce the abundance of infected nymphs by 67% in year 3 and 78% in year 5 (Mount et al. 1997). Treatment of 90% of the mice was estimated to result in only 56% reduction in the abundance of infected nymphs even after 10 yr of intervention. The method thus is sensitive both in terms of coverage of target rodent species and presence of alternative nontargeted *B. burgdorferi* reservoirs. Perhaps the greatest weakness in the existing set of field studies with rodent-targeted acaricide is lack of information on the local composition of tick hosts and *B. burgdorferi* reservoirs to clarify why the approach was highly successful in some areas but had very limited impact in other areas.

Rodent-Targeted Antibiotic Bait

A single published field study has evaluated the use of a rodent-targeted antibiotic bait to suppress host-seeking *B. burgdorferi*-infected *I. scapularis* nymphs in a New Jersey woodland setting (Dolan et al. 2011; Table 7). A doxycycline hyclate-laden bait delivered via rodent bait stations was shown to eliminate *B. burgdorferi* in rodent reservoirs and reduce infection by 92–94% in host-seeking nymphs after 1–2 yr of treatment in a woodland setting in New Jersey. The actual *B. burgdorferi* infection prevalence in nymphs collected from the treatment area was reduced from 37% in the year the intervention started—reflecting infections acquired by larvae fed in the preceding year before the intervention started—to <2% after 1–2 yr. Notable weaknesses for this strategy as a single control method include that it does not reduce tick abundance or risk of nuisance tick bites, and that the efficacy can be impacted locally by reservoirs that are unlikely to consume rodent-targeted bait delivered via bait boxes (e.g., shrews and birds). There also are concerns about the potential for development of microbial resistance after long-term use of a frontline antibiotic to treat infected rodents in the field. There are currently no efforts to commercialize this control method.

Rodent-Targeted Oral Vaccine Bait

Following a proof-of-concept field study in which white-footed mice were successfully needle-vaccinated against *B. burgdorferi* (Tsao et al. 2004), there was substantial interest in the development of an oral rodent reservoir-targeted vaccine against *B. burgdorferi* (Gomes-Solecki et al. 2006, Scheckelhoff et al. 2006, Bhattacharya et al. 2011, Meirelles Richer et al. 2011, Voordouw et al. 2013). No such vaccine is yet commercially available, although one may be on the horizon.

To date, there is only a single published field study on the use of a rodent-targeted oral vaccine to suppress host-seeking *B. burgdorferi*-infected *I. scapularis* nymphs, conducted in a woodland setting in New York (Meirelles Richer et al. 2014). Although showing promise with reduction in infection rates in host-seeking nymphs >85% in one of the intervention sites by years 3–4 after the intervention started (Table 7), the study also raised questions about the oral vaccine delivery mechanism and the interpretation of the results. The oral vaccine bait was produced daily and distributed via rodent live traps. This delivery scheme is in stark contrast to a realistic scenario where a field-formulated oral vaccine bait likely would be stored for some period of time before being used, and then offered to rodent reservoirs via a bait box to preclude ingestion by domestic animals or children (Telford et al. 2011). It cannot be ruled out that a more realistic oral vaccine delivery scheme would have impacted the observed efficacy of the intervention.

The most disappointing aspects of the field intervention study were that a substantial reduction (>50%) in the prevalence of infection for host-seeking nymphs often did not occur in the treatment plots in the first 1–2 yr after the intervention started, and that actual *B.*

burgdorferi infection rates of 25–45% were still recorded for nymphs in the four treatment plots 2 yr after oral vaccine deployment was started (Table 7). These results are not surprising, as the percentage of mice in the treatment plots that were considered to have achieved protective antibody levels were low, ranging from 10–33% (Meirelles Richer et al. 2014). A recent model projects that use of a mouse-targeted oral vaccine with 50% vaccination effectiveness would reduce *B. burgdorferi* infection rates in host-seeking nymphs by 56% (Tsao et al. 2012). Although a sustained effort to orally vaccinate reservoirs against *B. burgdorferi* will gather strength over time as the enzootic transmission cycle successively weakens (Voordouw et al. 2013, Meirelles Richer et al. 2014), the limited impact in the first 1–2 yr after the intervention is started is unfortunate. Other notable weaknesses for this strategy as a single control method include that it does not reduce tick abundance or risk of nuisance tick bites, that it does not reduce risk of exposure to more than one, albeit the most important one, of the suite of *I. scapularis*-borne human pathogens, and that the efficacy can be impacted locally by reservoirs that are unlikely to be vaccinated (e.g., shrews and birds). Additional field studies, including ones that use realistically field-formulated and delivered oral vaccine baits in residential settings, are needed.

Deer Reduction

The importance of the white-tailed deer (hereafter called deer) as a host for *I. scapularis* adults and amplifier for *I. scapularis* populations was recognized early on (Piesman et al. 1979, Main et al. 1981, Spielman et al. 1985, Spielman 1994). Early observational studies indicated that *I. scapularis* immatures were most abundant where deer were common but less abundant in settings with few or no deer (Wilson et al. 1985, 1990; Anderson et al. 1987; Duffy et al. 1994). Experimental studies showed that complete removal of deer from islands ultimately resulted in very low abundance of *I. scapularis* and dramatically reduced the abundance of host-seeking *B. burgdorferi*-infected ticks (Spielman 1988, Wilson et al. 1988, Telford 2002, Rand et al. 2004, Elias et al. 2011). The expected minimum time-lag between deer reduction and a substantial effect on the abundance of host-seeking nymphs is 2–3 yr. Because the abundance of host-seeking adults is directly impacted by removal of adults when they encounter a deer host (Ginsberg and Zhioua 1999), focusing on immatures is preferable when assessing the impact of deer reduction on tick population dynamics.

Several studies have attempted to clarify the association between deer density and abundance of *I. scapularis* ticks (Wilson et al. 1985, Deblinger et al. 1993, Rand et al. 2003, Stafford et al. 2003, Jordan et al. 2007, Kilpatrick et al. 2014). This undertaking is complicated by the multiyear life cycle of the tick (Yuval and Spielman 1990), especially for studies where deer were incrementally removed in a given area over time (Deblinger et al. 1993, Stafford et al. 2003, Jordan et al. 2007, Kilpatrick et al. 2014). Annual variations in weather conditions and host availability for immatures dramatically impact *I. scapularis* population dynamics, and may mask the impact of deer density on tick abundance. Moreover, variable methodologies used to assess deer density preclude reliable statistical analyses drawing on data from multiple studies. Nevertheless, the emerging consensus is that the relationship between deer density and host acquisition success by *I. scapularis* females is nonlinear, such that a threshold deer density may exist above which deer reduction has little impact on the tick population dynamics but below which deer reduction likely is accompanied by time-lagged reduction in the abundance of host-seeking *I. scapularis*. Therefore, high local deer density may explain results of studies where deer density, or factors related to deer density (deer browse, deer trails, or hunter kills), were not positively associated with abundance of host-seeking *I. scapularis* nymphs or *B. burgdorferi*-infected nymphs in space or over time (Wilson et al. 1984, Schulze et al. 2001c, Jordan and Schulze 2005, Ostfeld et al. 2006a).

As deer do not contribute directly as reservoirs of *B. burgdorferi* (Telford et al. 1988), the argument has been made that increasing deer density may result in decreased intensity of enzootic *B. burgdorferi* transmission due to immatures being diverted from feeding on rodent reservoirs to nonreservoir deer (Perkins et al. 2006). Field evidence rather show that deer density is positively associated with both numbers of *I. scapularis* immatures infesting rodent reservoirs (Wilson et al. 1985, 1988, 1990; Deblinger et al. 1993; Rand et al. 1994; Stafford et al. 2003) and abundance of host-seeking *B. burgdorferi*-infected nymphs (Kilpatrick et al. 2014, Werden et al. 2014).

The density to which deer need to be reduced in order to achieve a desired level of reduction in abundance of host-seeking nymphs and infected host-seeking nymphs unfortunately remains unclear. There are few experimental deer reduction studies that can shed light on this issue, in part due to lack of data from comparison areas in most deer reduction studies (Table 8). A reduction in deer density to below 40/km^2 resulted in a mere 12% decrease in the abundance of host-seeking nymphs, as compared with a control site, 2 years after the deer reduction effort (Jordan et al. 2007; Table 8). Infestation of *I. scapularis* nymphs on rodents decreased by 35–41% from preintervention levels 3–4 yr after estimated deer density fell below 25/km^2 in a coastal mainland site (Deblinger et al. 1993). Other studies where comparison sites unfortunately were lacking are suggestive of that reducing estimated deer density to ~25/km^2 is inadequate to suppress the abundance of host-seeking nymphs but that reduction to ~5/km^2 may have potential to achieve strong suppression (Stafford et al. 2003, Kilpatrick et al. 2014). Reduction of deer density to ~5/km^2 resulted in abundance of host-seeking nymphs in a residential setting in the spring of the following 2–4 yr of <0.7/100 m^2, and abundance of *B. burgdorferi*-infected host-seeking nymphs of <0.1/100 m^2 (Table 8). On islands where deer were nearly or completely eliminated, there was a 70% reduction in nymphal infestation on rodents, as compared with a control islands, 2 yr after deer density fell below 2.5/km^2 on Great Island (Wilson et al. 1988) and 100% reduction in nymphal infestation on rodents 3–4 yr after elimination was achieved on Monhegan Island (Rand et al. 2004). However, *I. scapularis* can persist at low abundance even in the complete absence of deer due to presence of alternative hosts for the adult stage (Fish and Dowler 1989) or repeated importation of immatures feeding on birds (Elias et al. 2011).

Stafford (2007) suggested that a reduction in deer density below ~3/km^2 (~8/square mile) may impact the population dynamics of *I. scapularis* to the point where enzootic transmission of *B. burgdorferi* is severely suppressed or drastically interrupted due to a reduction of immature ticks infesting spirochete-infected reservoir hosts. This idea is supported in part by simulation modeling, which projects that a reduction in deer density from 25/km^2 to 2.5/km^2 would reduce the abundance of *B. burgdorferi*-infected *I. scapularis* nymphs by ~65% after 5 yr and by 72% after 10 yr (Mount et al. 1997). Reducing deer density from 25/km^2 to 7.5/km^2 was projected to result in a 43% reduction in the abundance of infected nymphs after 10 yr, whereas reducing deer density from 25/km^2 to 0.25/km^2 was projected to result in a 74% reduction of infected nymphs after 3 yr, 88% after 5 yr, and 98% after 10 yr (Mount et al. 1997). Additional empirical studies are needed to clarify thresholds below which deer density need to be reduced in order to achieve: 1) reduced abundance of host-seeking nymphs; and more importantly 2) dramatically reduced abundance of infected host-seeking nymphs (resulting from loads of immature ticks on rodent reservoirs decreasing to the point where enzootic *B. burgdorferi* transmission is severely impacted).

Deer Exclusion

Although a deer fence will not prevent entry by small mammals or birds carrying larval ticks and only offers protection within the fenced area, it may provide long-term reductions of host-seeking *I. scapularis* nymphs (Table 9). Long-term (>5 yr) deer fencing of areas at least 3 ha in size typically has yielded a >45% reduction of host-seeking nymphs within fenced areas as compared with outside the fenced areas, including a >75% reduction of host-seeking ticks within fenced residential areas in New York (Daniels et al. 1993, Stafford 1993, Daniels and Fish 1995). The impact on the density of *B. burgdorferi*-infected nymphs was of the same magnitude (Daniels et al. 1993, Stafford 1993). Deer fencing in a residential setting resulted in abundance of host-seeking nymphs of <2/100 m^2, and abundance of *B. burgdorferi*-infected host-seeking nymphs of ≤0.2/100 m^2 (Table 9). For smaller (0.95–1.23 ha) deer exclosures in woodlands on Fire Island, New York, reduction in host-seeking *I. scapularis* nymphs was less pronounced and not even significant in all study years within the first 5 years after the exclosures were built (Ginsberg et al. 2004; Table 9). The effect of deer exclusion on populations of other tick species, including *I. ricinus* and *A. americanum*, similarly has been linked to the size of the exclosure area, with stronger reduction for larger deer exclusion areas (Bloemer et al. 1986, 1990; Ginsberg et al. 2002; Perkins et al. 2006).

Deer-Targeted Acaricides

Limited public acceptance of deer reduction led to an alternative approach by which deer are removed from the population of animals contributing to tick feeding by being treated with a topical acaricide rather than killed. Early work in the United States to develop and test devices for topical application of acaricide to deer is described by Sonenshine et al. (1996) and Pound et al. (2000, 2009a). This research led to the development of a device for topical application of acaricide to deer to control ticks—the United States Department of Agriculture's "4-Poster" deer feeder (Table 10). This device includes a food bait source (e.g., whole kernel corn) to attract deer, and while feeding they self-apply acaricide from treated rollers to their head, ears, and neck (Pound et al. 2000).

Initial proof-of-concept studies with the 4-poster device showed that it dramatically reduced adult tick feeding on deer and also reduced the abundance of host-seeking *I. scapularis* nymphs by 69–91% following a 2–3 yr deployment period (Carroll et al. 2002, Solberg et al. 2003). Additional studies evaluated the use of the 4-poster device to control *I. scapularis* on inhabited islands (Carroll et al. 2009a,b; Grear et al. 2014) as well as in mainland wooded areas (Carroll et al. 2009a, Schulze et al. 2009) and residential settings (Carroll et al. 2009a, Daniels et al. 2009, Miller et al. 2009, Stafford et al. 2009; Table 10). A meta-analysis of a suite of five linked studies in Rhode Island, Connecticut, New York, New Jersey, and Maryland within the "Northeast Area-Wide Tick Control Project (NEATCP)" (Carroll et al. 2009a, Daniels et al. 2009, Miller et al. 2009, Schulze et al. 2009, Stafford et al. 2009) concluded that the overall reduction in abundance of host-seeking *I. scapularis* nymphs within areas with a high density of 4-poster devices (1 per 20–25 ha) approached 50% by the third year after the intervention began and reached 60 and 70% in the fourth and sixth years, respectively (Brei et al. 2009, Pound et al. 2009b). There was no significant impact on the prevalence of infection with *B. burgdorferi* in host-seeking *I. scapularis* nymphs within the treatment areas (Gatewood Hoen et al. 2009). The lack of an impact on the prevalence of infection in host-seeking *I. scapularis* nymphs with *B. burgdorferi* following 4-poster device deployment is disappointing, as it indicates that the interventions failed to reduce the burden of *I. scapularis* immatures on rodent reservoirs to the point where it negatively impacted enzootic *B. burgdorferi* transmission.

The results from individual studies vary with density of 4-poster devices deployed as well as among study sites using the same deployment density of 4-poster devices. High density 4-poster device deployments (1 device per 20–25 ha) in mainland residential settings in Connecticut and New York resulted in 63–64% reduction of host seeking *I. scapularis* nymphs by the 4th year after the intervention started and 70–80% by the 6th year (Daniels et al. 2009, Stafford et al. 2009). However, a parallel study performed in a mainland residential setting in Rhode Island using a similar deployment density of 4-poster devices failed to provide reductions in abundance of host-seeking *I. scapularis* nymphs above 55% (Miller et al. 2009). This contrasting result was likely attributable to alternative competing food sources, such as hay fields and acorns during oak masting years, which presumably resulted in decreased use by deer of the 4-poster devices as compared with companion studies conducted in Connecticut and New York. Grear et al. (2014) attempted a deployment strategy with a much lower density of 4-poster devices (~1/60 ha) in three locations in Massachusetts. This deployment density failed to reduce the abundance of host-seeking *I. scapularis* nymphs by more than 10% over a 5-yr period. Based on data from a meta-analysis of multiple studies in residential and woodland settings, use of topical acaricide for deer resulted in abundance of *B. burgdorferi*-infected host-seeking nymphs of <0.1/100 m^2 after 4–6 yr (Table 10).

It is interesting to compare the outcomes of the 4-poster device field intervention studies with simulation modeling projections for this control method (Mount et al. 1997), albeit with the caveat that the simulation modeling assumed that 4-poster devices were continuously operated from March through November as opposed to only being used during typical adult tick activity periods in the spring and fall. The simulation model projected that treatment of 90% of the deer, with 95% tick mortality on treated animals, would reduce the abundance of *B. burgdorferi*-infected *I. scapularis* nymphs by 87% after 3 yr and 95% after 5 yr (Mount et al. 1997). Actual outcomes of field intervention studies are in the range of 50% reduction after 3 yr and 60% after 5 yr (Brei et al. 2009, Gatewood Hoen et al. 2009), which is in line with a simulation model projection based on treatment of between 50–70% of the deer.

Potential problems with use of the 4-poster device include label restrictions, variable homeowner acceptance leading to patchy deployment, regulatory issues preventing placement in optimal locations and during optimal time periods (peak adult activity periods), interference with devices by nontarget mammals such as tree squirrels and raccoons, acorn mast providing a competing food source in some years, spatial variability in alternative food sources such as hay fields, the contribution to tick feeding by nontreated deer, and light application of acaricide allowing ticks to feed successfully even on treated animals (Carroll et al. 2008, 2009a; Miller et al. 2009; Stafford et al. 2009). Additional concerns include strict regulation for use of devices that serve to aggregate deer, for example by using food bait as in the 4-poster device, based on increased potential for spread of pathogens that are transmitted by contact with saliva or blood from infected animals. Although use of the 4-poster device holds promise as an environmentally friendly large-scale intervention method, we do not yet know enough about the extent to which local ecology combined with logistical and regulatory constraints may complicate community-driven implementation. Finally, a host-targeted strategy focusing on treating deer with acaricides should draw the most concern regarding potential emergence of pesticide resistance in *I. scapularis*, particularly if used successfully across wide areas.

Additional Deer-Targeted Approaches

Two additional deer-targeted approaches warrant discussion: 1) oral ingestion of a development inhibitor or systemic acaricide that prevents *I. scapularis* females from either feeding to completion or laying viable eggs; and 2) an antitick vaccine for deer against *I. scapularis*. On a Maine coastal island, ivermectin-treated corn made available to deer failed to suppress *I. scapularis* immatures on rodents and host-seeking adults despite reduced infestation by adults on deer with elevated serum ivermectin levels as well as reduced fecundity of female ticks known to have fed on these deer (Rand et al. 2000). This type of approach merits additional investigation utilizing an intensive distribution of bait treated with ivermectin or other emerging oral development inhibitors or systemic acaricides in order to achieve higher levels of protection in the overall deer population. The notion of an anti-*I. scapularis* vaccine for deer, similar to the anti-*Rhipicephalus* (*Boophilus*) *microplus* (Canestrini) vaccines developed for cattle (Merino et al. 2013), is intriguing, as it may circumvent many of the problems encountered with deer reduction or use of topical acaricides on deer. The primary logistical problem, should it be feasible to develop such a vaccine, lies in the delivery of such a vaccine to deer.

Integrated Tick and Pathogen Management for Suppression of *I. scapularis* and *B. burgdorferi*

Integrated pest management combines two or more control methods and aims to reduce distribution of chemicals in the environment. Several authors have discussed how the concept of integrated pest management can be applied to suppression of *I. scapularis* and *B. burgdorferi* (Mount et al. 1997, Ginsberg 2001, Ostfeld et al. 2006b, Stafford 2007, Pérez de León 2014). Some have called this integrated tick management but an approach that combines methods to both kill *I. scapularis* as well as prevent infection with or kill *B. burgdorferi* in rodent reservoirs without killing ticks is perhaps better termed integrated tick and pathogen management. Published literature on the use of integrated tick and pathogen management strategies to suppress *I. scapularis* is very limited (Table 11), and no published studies have included outcomes for the density of *B. burgdorferi*-infected *I. scapularis* nymphs.

Two studies have an element of integrated management by combining a nontreated wood chip barrier with spray application of entomopathogenic fungi (Stafford and Allan 2010) or a natural product-based chemical acaricide (nootkatone) with entomopathogenic fungi (Bharadwaj et al. 2012). The addition of a nontreated wood chip barrier appeared to enhance reduction of host-seeking nymphs compared with use of *B. bassiana* alone. This effect, however, was not consistent across *B. bassiana* strains or treatment years (Stafford and Allan 2010). Bharadwaj et al. (2012) found no evidence of a beneficial effect of adding entomopathogenic fungi with nootkatone spray applications as compared with use of nootkatone alone. Both these studies combined different methods to control host-seeking nymphs rather than using an integrated tick and pathogen management strategy to attack the tick in multiple life stages or activity states.

Schulze et al. (2007, 2008b) evaluated the integrated use of a barrier spray along the woods and lawn edge using the synthetic acaricide deltamethrin (Year 1 only) with topical acaricide applications targeted to rodents using fipronil (MaxForce TMS; Years 1–2 only) and deer using amitraz (4-Poster device; Years 1–3) to suppress *I. scapularis* in a residential landscape. This multipronged intervention attacked both immature and adult tick stages as well as host-seeking ticks and ticks on hosts, and the successive withdrawal of methods served to minimize the amount of acaricide used. The abundance of host-seeking nymphs was reduced by 86% in the year after the intervention was put in place and by 86–94% in the two following years. The resulting abundances of host-seeking nymphs were <2/100 m^2 (Table 11). Infection of host-seeking nymphs with *B. burgdorferi* was not assessed.

To address the major knowledge gap for the potential of integrated tick and pathogen management strategies to suppress *B. burgdorferi*-infected *I. scapularis* nymphs in residential settings, the Centers for Disease Control and Prevention funded two cooperative agreements under the broad heading: “Ability of individual and integrated tick management technologies to reduce the entomological risk of Lyme disease.” In addition to assessing the impact of single versus integrated control strategies on the density of host-seeking infected nymphs, these projects also include assessments of cost and acceptability of the evaluated control methods. The projects are nearing completion and results will soon be forthcoming. Additional studies on the potential of different integrated tick and pathogen management strategies to suppress *B. burgdorferi*-infected *I. scapularis* nymphs are urgently needed.

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Table 1

Percent reduction for *I. scapularis* collected on treated versus nontreated clothing or tick drags in a field setting

Active ingredient and type of treated textile	Concentration of active ingedient	Application method	Timing of evaluation after treatment	Total exposure	Life stage	Tick contact per 100 m (unless otherwise specified)		% reduction in tick contact for treatment[a]	Reference
						Treatment	Control		
Deet									
Military uniform	20% deet	Spray	1–5 d	12 man-hours activity	Nymph	0.25 / h	1.5 / h	83	Schreck et al. 1986
Military uniform	30% deet	Spray	1–5 d	12 man-hours activity	Nymph	0 / h	1.5 / h	100	Schreck et al. 1986
Military uniform	20% deet	Spray	1–5 d	12 man-hours activity	Adult	1.5 / h	10.6 / h	86	Schreck et al. 1986
Military uniform	30% deet	Spray	1–5 d	12 man-hours activity	Adult	1.1 / h	10.6 / h	90	Schreck et al. 1986
Nootkatone									
Tick drag	9.8% nootkatone	Spray	1 d	500 m dragging	Nymph	0	5.4	100	Schulze et al. 2011
Tick drag	9.8% nootkatone	Spray	3 d	500 m dragging	Nymph	0	7.2	100	Schulze et al. 2011
Tick drag	9.8% nootkatone	Spray	14 d	500 m dragging	Nymph	0	3.2	100	Schulze et al. 2011
Coveralls	10% nootkatone	Spray	1 d	1,200 m walking	Adult	0	9.1	100	Jordan et al. 2012
Coveralls	10% nootkatone	Spray	2 d	1,200 m walking	Adult	0	8.3	100	Jordan et al. 2012
Coveralls	10% nootkatone	Spray	3 d	1,200 m walking	Adult	0	7.8	100	Jordan et al. 2012
Coveralls	10% nootkatone	Spray	7 d	1,200 m walking	Adult	2.3	9.5	76	Jordan et al. 2012
Carvacrol									
Tick drag	9.5% carvacrol	Spray	1 d	500 m dragging	Nymph	0	12.6	100	Schulze et al. 2011
Tick drag	9.5% carvacrol	Spray	3 d	500 m dragging	Nymph	0	7.2	100	Schulze et al. 2011
Tick drag	9.5% carvacrol	Spray	14 d	500 m dragging	Nymph	0.8	8.6	91	Schulze et al. 2011
Coveralls	9.5% carvacrol	Spray	1 d	1,200 m walking	Adult	0	9.1	100	Jordan et al. 2012
Coveralls	9.5% carvacrol	Spray	2 d	1,200 m walking	Adult	0.7	8.3	92	Jordan et al. 2012
Coveralls	9.5% carvacrol	Spray	3 d	1,200 m walking	Adult	2.8	7.8	64	Jordan et al. 2012
Coveralls	9.5% carvacrol	Spray	7 d	1,200 m walking	Adult	6.1	9.5	36	Jordan et al. 2012
Combinations of essential oils[b]									
Tick drag	0.19 mg AI / cm^2	Spray	1 d	500 m dragging	Nymph	0	12.6	100	Schulze et al. 2011
Tick drag	0.19 mg AI / cm^2	Spray	3 d	500 m dragging	Nymph	0.6	7.2	92	Schulze et al. 2011
Tick drag	0.19 mg AI / cm^2	Spray	14 d	500 m dragging	Nymph	0.2	8.6	98	Schulze et al. 2011
Coveralls	0.25 mg AI / cm^2	Spray	1 d	1,200 m walking	Adult	0.5	9.1	94	Jordan et al. 2012

Active ingredient and type of treated textile	Concentration of active ingedient	Application method	Timing of evaluation after treatment	Total exposure	Life stage	Tick contact per 100 m (unless otherwise specified)		% reduction in tick contact for treatment[a]	Reference
						Treatment	Control		
Coveralls	0.25 mg AI / cm^2	Spray	2 d	1,200 m walking	Adult	0.3	8.3	96	Jordan et al. 2012
Coveralls	0.25 mg AI / cm^2	Spray	3 d	1,200 m walking	Adult	0.7	7.8	91	Jordan et al. 2012
Coveralls	0.25 mg AI / cm^2	Spray	7 d	1,200 m walking	Adult	3.0	9.5	68	Jordan et al. 2012
Permethrin									
Military uniform	0.5% permethrin	Spray	1–5 d	12 man-hours activity	Nymph	0 / h	1.5 / h	100	Schreck et al. 1986
Military uniform	0.5% permethrin	Spray	1–5 d	12 man-hours activity	Adult	0 / h	10.6 / h	100	Schreck et al. 1986
Coveralls	0.5% permethrin	Spray	1 d	1,200 m walking	Adult	0.2	9.1	98	Jordan et al. 2012
Coveralls	0.5% permethrin	Spray	2 d	1,200 m walking	Adult	0.2	8.3	98	Jordan et al. 2012
Coveralls	0.5% permethrin	Spray	3 d	1,200 m walking	Adult	2.4	7.8	69	Jordan et al. 2012
Coveralls	0.5% permethrin	Spray	7 d	1,200 m walking	Adult	2.6	9.5	73	Jordan et al. 2012
Tick drag	0.5% permethrin	Spray	1 d	500 m dragging	Nymph	0	12.6	100	Schulze et al. 2011
Tick drag	0.5% permethrin	Spray	3 d	500 m dragging	Nymph	0	7.2	100	Schulze et al. 2011
Tick drag	0.5% permethrin	Spray	14 d	500 m dragging	Nymph	0	8.6	100	Schulze et al. 2011

[a] Calculated based on comparison of values for treatment and control. Set to 100% when ticks were recorded in the control but not in the treatment.

[b] Combinations of different essential oils, including, among others, rosemary, geraniol, cinnamon leaf, lemongrass, and wintergreen.

Table 2

Percent reduction postintervention in abundance of *I. scapularis* nymphs and abundance of *B. burgdorferi*-infected nymphs, and end-point values for these measures, for single intervention methods based on vegetation management

Type of vegetation management intervention	Timing of intervention	Setting	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Percent reduction relative to control sites (CS) and abundance of host-seeking infected nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Reference
				%reduction in TS	Abundance in TS	% reduction in TS	Abundance in TS	
Leaf litter removal	March	Woodland	13–15 wk	75[a]	Not clear	No data	No data	Schulze et al. 1995
Leaf litter removal	June	Woodland	1–2 wk	77[a]	Not clear	No data	No data	Schulze et al. 1995
Burn	April	Woodland	10–11 wk	50[a]	97.2 / h	4[a]	34.0 / h	Mather et al. 1993
Burn, less intense	April	Woodland	<1 to 4 mo	74[a]	0.3	Not shown[b]	Not shown[b]	Stafford et al. 1998
Burn, more intense	May	Woodland	<1 to 3 mo	97[a]	0.03	Not shown[b]	Not shown[b]	Stafford et al. 1998

All studies were conducted in the northeastern United States.

[a]Calculated based on comparison of postintervention treatment site value and postintervention control site value.

[b]Data not shown due to very small sample sizes for nymphs examined for presence of *B. burgdorferi* from treatment areas.

Table 3

Percent reduction postintervention in abundance of *I. scapularis* nymphs, and end-point values for nymphal abundance, for single intervention methods based on application of synthetic chemical acaricides to the environment

Synthetic chemical acaricide used	Mode of application	Spray pressure	Type of application	Application scheme	Amount or concentration of active ingredient (AI) applied	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h		Percent reduction in infestation of rodents by nymphs (no. nymphs per animal) in treatment sites after intervention	Reference
									% reduction in TS	Abundance in TS		
Pyrethroid												
Bifenthrin	Spray	Low	Ground	Single, June	115 g AI/ha	Residential	2000	2–6 wk	87[a]	0.1	No data	Stafford and Allan 2010
Bifenthrin	Spray	High	Ground	Single, May	115 g AI/ha	Residential	1999	2–6 wk	86[a]	0.2	No data	Stafford and Allan 2010
Bifenthrin	Spray	High	Ground	Single, July	254 g AI/ha	Woodland	–	1 wk	100[b]	0	No data	Rand et al. 2010
Bifenthrin	Spray	High	Ground	Single, July	254 g AI/ha	Woodland	–	2 wk	100[b]	0	No data	Rand et al. 2010
Bifenthrin	Spray	High	Ground	Single, July	254 g AI/ha	Woodland	–	1 wk	100[a]	0	No data	Elias et al. 2013
Bifenthrin	Spray	High	Ground	Single, July	254 g AI/ha	Woodland	–	2 wk	100[a]	0	No data	Elias et al. 2013
Bifenthrin	Spray	High	Ground	Single, July	254 g AI/ha	Woodland	–	4 wk	100[a]	0	No data	Elias et al. 2013
Bifenthrin	Spray	Variable	Ground	Single, May–June	127–254 g AI/ha	Residential	2011	3–4 wk	69[b]	8.5 / h	No data	Hinckley et al. 2016
Bifenthrin	Spray	Variable	Ground	Single, April–June	127–254 g AI/ha	Residential	2012	3–4 wk	45[b]	4.2 / h	No data	Hinckley et al. 2016
Cyfluthrin	Spray	Low	Ground	Single, May	410 g AI/ha	Woodland	–	~1 wk	96[a]	0.7	No data	Solberg et al. 1992
Cyfluthrin	Spray	Low	Ground	Single, May	410 g AI/ha	Woodland	–	~8 wk	100[a]	0	No data	Solberg et al. 1992
Cyfluthrin	Spray	High	Ground	Single, June	100 g AI/ha	Residential	–	~2 wk	95[b]	0.02	No data	Curran et al. 1993
Cyfluthrin	Spray	High	Ground	Single, June	100 g AI/ha	Residential	–	~4 wk	88[b]	0.11	No data	Curran et al. 1993
Cyfluthrin	Spray	High	Ground	Single, June	100 g AI/ha	Residential	–	~6 wk	93[b]	0.02	No data	Curran et al. 1993
Cyfluthrin	Granules	–	Ground	Single, May	410 g AI/ha	Woodland	–	~1 wk	97[a]	0.5	No data	Solberg et al. 1992
Cyfluthrin	Granules	–	Ground	Single, May	410 g AI/ha	Woodland	–	~8 wk	87[a]	0.9	No data	Solberg et al. 1992

Synthetic chemical acaricide used	Mode of application	Spray pressure	Type of application	Application scheme	Amount or concentration of active ingredient (AI) applied	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h		Percent reduction in infestation of rodents by nymphs (no. nymphs per animal) in treatment sites after intervention	Reference
									% reduction in TS	Abundance in TS		
Deltamethrin	Granules	–	Ground	Single, June	150 g AI/ha	Residential	–	~1 wk	95[a]	0.3	No data	Schulze et al. 2001b
Deltamethrin	Granules	–	Ground	Single, May	150 g AI/ha	Residential	–	1 wk	99[a]	0.1	No data	Schulze et al. 2005
Deltamethrin	Granules	–	Ground	Single, May	150 g AI/ha	Residential	–	2 wk	99[a]	0.1	No data	Schulze et al. 2005
Deltamethrin	Granules	–	Ground	Single, May	150 g AI/ha	Residential	–	3 wk	97[a]	0.2	No data	Schulze et al. 2005
Deltamethrin	Granules	–	Ground	Single, May	150 g AI/ha	Residential	–	4 wk	100[a]	0	No data	Schulze et al. 2005
Deltamethrin	Granules	–	Ground	Single, May	150 g AI/ha	Residential	–	5 wk	100[a]	0	No data	Schulze et al. 2005
Cyfluthrin	Spray	Low	Ground	Single, November	410 g AI/ha	Woodland	Fall application	6.5 mo	38[b]	1.2	No data	Solberg et al. 1992
Cyfluthrin	Granules	–	Ground	Single, November	410 g AI/ha	Woodland	Fall application	6.5 mo	57[b]	0.8	No data	Solberg et al. 1992
Deltamethrin	Spray	High	Ground	Single, October	90 g AI/ha	Woodland	Fall application, 04	6.5–7.5 mo	80[a]	1.7	No data	Schulze et al. 2008a
Deltamethrin	Spray	High	Ground	Single, October	90 g AI/ha	Woodland	Fall application, 05	6.5–7.5 mo	100[a]	0	No data	Schulze et al. 2008a
Deltamethrin	Spray	High	Ground	Single, October	90 g AI/ha	Woodland	Fall application, 06	6.5–7.5 mo	100[a]	0	No data	Schulze et al. 2008a
Organophosphate												
Chlorpyrifos	Spray	Low	Ground	Single, June	0.6 kg AI/ha	Woodland	–	1 wk	100[a]	0	No data	Allan and Patrican 1995
Chlorpyrifos	Spray	Low	Ground	Single, June	0.6 kg AI/ha	Woodland	–	2 wk	94[a]	0.6	No data	Allan and Patrican 1995
Chlorpyrifos	Spray	Low	Ground	Single, June	0.6 kg AI/ha	Woodland	–	6 wk	100[a]	0	No data	Allan and Patrican 1995
Chlorpyrifos	Spray	High	Ground	Single, May	0.6 kg AI/ha	Residential	–	~2 wk	97[b]	0.02	No data	Curran et al. 1993
Chlorpyrifos	Spray	High	Ground	Single, May	0.6 kg AI/ha	Residential	–	~4 wk	84[b]	0.07	No data	Curran et al. 1993
Chlorpyrifos	Spray	High	Ground	Single, May	0.6 kg AI/ha	Residential	–	~6 wk	85[b]	0.07	No data	Curran et al. 1993
Chlorpyrifos	Spray	High	Ground	Single, May	1.1 kg AI/ha	Residential	–	~2 wk	95[b]	0.05	No data	Curran et al. 1993
Chlorpyrifos	Spray	High	Ground	Single, May	1.1 kg AI/ha	Residential	–	~4 wk	100[b]	0	No data	Curran et al. 1993

Synthetic chemical acaricide used	Mode of application	Spray pressure	Type of application	Application scheme	Amount or concentration of active ingredient (AI) applied	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h		Percent reduction in infestation of rodents by nymphs (no. nymphs per animal) in treatment sites after intervention	Reference
									% reduction in TS	Abundance in TS		
Chlorpyrifos	Spray	High	Ground	Single, May	1.1 kg AI/ha	Residential	–	~6 wk	96[b]	0.02	No data	Curran et al. 1993
Chlorpyrifos	Granules	–	Ground	Single, June	1.1 kg AI/ha	Residential	–	~2 wk	96[b]	0.02	No data	Curran et al. 1993
Chlorpyrifos	Granules	–	Ground	Single, June	1.1 kg AI/ha	Residential	–	~4 wk	90[b]	0.06	No data	Curran et al. 1993
Chlorpyrifos	Granules	–	Ground	Single, June	1.1 kg AI/ha	Residential	–	~6 wk	100[b]	0	No data	Curran et al. 1993
Chlorpyrifos	Granules	–	Ground	Dual, June–July	1.1 kg AI/ha	Woodland	1989	1wk–3 mo	No data	No data	81[a]	Schulze et al. 1991
Diazinon	Granules	–	Ground	Dual, June–July	4.5 kg AI/ha	Woodland	1989	1wk–3 mo	No data	No data	54[a]	Schulze et al. 1991
Carbamate												
Carbaryl	Spray	High	Ground	Single, June	0.6 kg AI/ha	Residential	–	~2 wk	69[b]	0.16	No data	Curran et al. 1993
Carbaryl	Spray	High	Ground	Single, June	0.6 kg AI/ha	Residential	–	~4 wk	86[b]	0.11	No data	Curran et al. 1993
Carbaryl	Spray	High	Ground	Single, June	0.6 kg AI/ha	Residential	–	~6 wk	86[b]	0.05	No data	Curran et al. 1993
Carbaryl	Spray	High	Ground	Single, June	1.1 kg AI/ha	Residential	–	~2 wk	76[b]	0.33	No data	Curran et al. 1993
Carbaryl	Spray	High	Ground	Single, June	1.1 kg AI/ha	Residential	–	~4 wk	87[b]	0.05	No data	Curran et al. 1993
Carbaryl	Spray	High	Ground	Single, June	1.1 kg AI/ha	Residential	–	~6 wk	64[b]	0.19	No data	Curran et al. 1993
Carbaryl	Spray	High	Ground	Single, June	1.5–2.1 kg AI/ha	Residential	–	2–3 wk	93[a]	Not clear	No data	Stafford 1991a
Carbaryl	Spray	High	Ground	Single, June	1.5–2.1 kg AI/ha	Residential	–	4–5 wk	93[a]	Not clear	No data	Stafford 1991a
Carbaryl	Spray	High	Ground	Single, June	1.5–2.1 kg AI/ha	Residential	–	7–8 wk	91[a]	Not clear	No data	Stafford 1991a
Carbaryl	Spray	High	Ground	Single, June	1.5–2.1 kg AI/ha	Residential	–	9–10 wk	43[a]	Not clear	No data	Stafford 1991a
Carbaryl	Spray	High	Ground	Single, June	1.5–2.1 kg AI/ha	Residential	–	12–13 wk	72[a]	Not clear	No data	Stafford 1991a
Carbaryl	Granules	–	Ground	Single, June	4.5 kg AI/ha	Residential	–	2 wk	89[b]	0.15	No data	Curran et al. 1993
Carbaryl	Granules	–	Ground	Single, June	4.5 kg AI/ha	Residential	–	4 wk	70[b]	0.19	No data	Curran et al. 1993

Synthetic chemical acaricide used	Mode of application	Spray pressure	Type of application	Application scheme	Amount or concentration of active ingredient (AI) applied	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h		Percent reduction in infestation of rodents by nymphs (no. nymphs per animal) in treatment sites after intervention	Reference
									% reduction in TS	Abundance in TS		
Carbaryl	Granules	–	Ground	Single, June	4.5 kg AI/ha	Residential	–	6 wk	71[b]	0.18	No data	Curran et al. 1993
Carbaryl	Granules	–	Ground	Dual, June–July	2.0 kg AI/ha	Woodland	1990	1 wk–3 mo	No data	No data	62[a]	Schulze et al. 1991
Carbaryl	Granules	–	Ground	Dual, June–July	4.0 kg AI/ha	Woodland	1990	1 wk–3 mo	No data	No data	70[a]	Schulze et al. 1991
Carbaryl	Granules	–	Ground	Dual, June–July	8.3 kg AI/ha	Woodland	1989	1 wk–3 mo	No data	No data	100[b]	Schulze et al. 1991
Carbaryl	Granules	–	Ground	Dual, June–July	8.1 kg AI/ha	Woodland	1990	1 wk–3 mo	No data	No data	89[a]	Schulze et al. 1991
Carbaryl	Granules	–	Ground	Single, May	4.5 kg AI/ha	Woodland		1–5 wk	73[a]	Not clear	No data	Schulze et al. 2000
Carbaryl	Granules	–	Ground	Single, May	8.8 kg AI/ha	Residential	Lake Drive NE	4–5 wk	No data	No data	88[c]	Schulze et al. 1994
Carbaryl	Granules	–	Ground	Single, May	6.8 kg AI/ha	Residential	Lake Drive NW	4–5 wk	No data	No data	90[c]	Schulze et al. 1994
Carbaryl	Granules	–	Aerial	Single, June	6.8 kg AI/ha	Residential	Lake Drive SE	4–5 wk	No data	No data	84[c]	Schulze et al. 1994
Carbaryl	Granules	–	Aerial	Single, June	2.6 kg AI/ha	Residential	Lake Drive SW	4–5 wk	No data	No data	70[c]	Schulze et al. 1994
Carbaryl	Granules	–	Ground	Single, June	4.5 kg AI/ha	Residential	Sparse litter	<1 wk	91[a]	Not clear	No data	Schulze and Jordan 1995
Carbaryl	Granules	–	Ground	Single, June	4.5 kg AI/ha	Residential	Deeper litter	<1 wk	96[a]	Not clear	No data	Schulze and Jordan 1995
Carbaryl	Granules	–	Ground	Single, June	4.5 kg AI/ha	Residential	Sparse litter	7–8 wk	87[a]	Not clear	No data	Schulze and Jordan 1995
Carbaryl	Granules	–	Ground	Single, June	4.5 kg AI/ha	Residential	Deeper litter	7–8 wk	46[a]	Not clear	No data	Schulze and Jordan 1995

All studies were conducted in the northeastern United States.

[a]Calculated to account for pre- and posttreatment time point counts in both control and treatement areas, following Henderson and Tilton (1955) or Mount et al. (1976).

[b]Calculated based on comparison of postintervention treatment value and postintervention control value.

Table 4

Percent reduction postintervention in abundance of *I. scapularis* nymphs, and end-point values for nymphal abundance, for single intervention methods based on application of natural product-based chemical acaricides to the environment

Natural product-based chemical acaricide used	Mode of application	Spray pressure	Application scheme	Amount or concentration of active ingredient (AI) applied	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Reference
								%reduction in TS	Abundance in TS	
Pyrethrin										
Pyrethrin soap	Spray	Low	Single, June	0.9 kg AI/ha	Woodland	–	1 wk	95[a]	1.2	Allan and Patrican 1995
Pyrethrin soap	Spray	Low	Single, June	0.9 kg AI/ha	Woodland	–	2 wk	60[a]	6.0	Allan and Patrican 1995
Pyrethrin soap	Spray	Low	Single, June	0.9 kg AI/ha	Woodland	–	6 wk	23[a]	3.0	Allan and Patrican 1995
Pyrethrin soap	Spray	Low	Single, July	0.9 kg AI/ha	Woodland	–	1 wk	93[a]	0.8	Patrican and Allan 1995b
Pyrethrin soap	Spray	Low	Single, July	0.9 kg AI/ha	Woodland	–	2 wk	66[a]	2.0	Patrican and Allan 1995b
Pyrethrin soap	Spray	Low	Single, July	0.9 kg AI/ha	Woodland	–	3 wk	24[a]	2.4	Patrican and Allan 1995b
Pyrethrin soap + Isopropyl alcohol	Spray	Low	Single, July	0.8 kg AI/ha	Woodland	–	1 wk	100[a]	0	Patrican and Allan 1995b
Pyrethrin soap + Isopropyl alcohol	Spray	Low	Single, July	0.8 kg AI/ha	Woodland	–	2 wk	86[a]	0.8	Patrican and Allan 1995b
Pyrethrin soap + Isopropyl alcohol	Spray	Low	Single, July	0.8 kg AI/ha	Woodland	–	3 wk	33[a]	2.0	Patrican and Allan 1995b
Desiccant with pyrethrin	Dust	–	Single, June	0.6 kg AI/ha	Woodland	–	1 wk	88[a]	3.2	Allan and Patrican 1995
Desiccant with pyrethrin	Dust	–	Single, June	0.6 kg AI/ha	Woodland	–	2 wk	82[a]	3.0	Allan and Patrican 1995
Desiccant with pyrethrin	Dust	–	Single, June	0.6 kg AI/ha	Woodland	–	6 wk	29[a]	3.0	Allan and Patrican 1995

Natural product-based chemical acaricide used	Mode of application	Spray pressure	Application scheme	Amount or concentration of active ingredient (AI) applied	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Reference
								%reduction in TS	Abundance in TS	
Desiccant with pyrethrin	Dust	–	Single, July	0.6 kg AI/ha	Woodland	–	1 wk	100[a]	0	Patrican and Allan 1995b
Desiccant with pyrethrin	Dust	–	Single, July	0.6 kg AI/ha	Woodland	–	2 wk	79[a]	1.2	Patrican and Allan 1995b
Desiccant with pyrethrin	Dust	–	Single, July	0.6 kg AI/ha	Woodland	–	3 wk	33[a]	2.0	Patrican and Allan 1995b
Nootkatone										
Nootkatone	Spray	Low	Single, May	7.5 kg AI/ha	Woodland	2006	10 d	88[a]	1.5	Dolan et al. 2009
Nootkatone	Spray	Low	Single, May	7.5 kg AI/ha	Woodland	2006	2 wk	77[a]	3.0	Dolan et al. 2009
Nootkatone	Spray	Low	Single, May	7.5 kg AI/ha	Woodland	2006	3 wk	63[a]	4.0	Dolan et al. 2009
Nootkatone	Spray	Low	Single, May	7.5 kg AI/ha	Woodland	2006	4 wk	41[a]	6.0	Dolan et al. 2009
Nootkatone	Spray	Low	Single, June	7.6 kg AI/ha	Woodland	Core, 2008	1 wk	82[a]	3.2	Dolan et al. 2009
Nootkatone	Spray	Low	Single, June	7.6 kg AI/ha	Woodland	Core, 2008	2 wk	84[a]	2.6	Dolan et al. 2009
Nootkatone	Spray	Low	Single, June	7.6 kg AI/ha	Woodland	Core, 2008	3 wk	53[a]	5.8	Dolan et al. 2009
Nootkatone	Spray	Low	Single, June	7.6 kg AI/ha	Woodland	Core, 2008	4 wk	61[a]	4.8	Dolan et al. 2009
Nootkatone	Spray	Low	Single, June	7.6 kg AI/ha	Woodland	Core, 2008	5 wk	41[a]	4.6	Dolan et al. 2009
Nootkatone	Spray	Low	Single, June	7.6 kg AI/ha	Woodland	Core, 2008	6 wk	77[a]	1.2	Dolan et al. 2009
Nootkatone	Spray	Low	Single, May	39.4 kg AI/ha	Woodland	2007	1 wk	73[a]	3.8	Dolan et al. 2009
Nootkatone	Spray	Low	Single, May	39.4 kg AI/ha	Woodland	2007	2 wk	79[a]	3.2	Dolan et al. 2009
Nootkatone	Spray	Low	Single, May	39.4 kg AI/ha	Woodland	2007	3 wk	72[a]	5.2	Dolan et al. 2009
Nootkatone	Spray	Low	Single, May	39.4 kg AI/ha	Woodland	2007	4 wk	50[a]	6.6	Dolan et al. 2009
Nootkatone “nanoemulsion”	Spray	Low	Single, June	11.9 kg AI/ha	Woodland	2× diluent	1 wk	84[a]	4.0	Dolan et al. 2009
Nootkatone “nanoemulsion”	Spray	Low	Single, June	11.9 kg AI/ha	Woodland	2× diluent	2 wk	57[a]	6.4	Dolan et al. 2009

Natural product-based chemical acaricide used	Mode of application	Spray pressure	Application scheme	Amount or concentration of active ingredient (AI) applied	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Reference
								%reduction in TS	Abundance in TS	
Nootkatone “nanoemulsion”	Spray	Low	Single, June	11.9 kg AI/ha	Woodland	2× diluent	3 wk	70[a]	3.0	Dolan et al. 2009
Nootkatone “nanoemulsion”	Spray	Low	Single, June	11.9 kg AI/ha	Woodland	2× diluent	4 wk	86[a]	1.8	Dolan et al. 2009
Nootkatone “nanoemulsion”	Spray	Low	Single, June	11.9 kg AI/ha	Woodland	2× diluent	5 wk	92[a]	0.8	Dolan et al. 2009
Nootkatone “nanoemulsion”	Spray	Low	Single, June	11.9 kg AI/ha	Woodland	2× diluent	6 wk	43[a]	2.0	Dolan et al. 2009
Nootkatone	Spray	Low	Dual, June	7.6 kg AI/ha	Woodland	2009	1 wk	91[a]	1.2	Jordan et al. 2011
Nootkatone	Spray	Low	Dual, June	7.6 kg AI/ha	Woodland	2009	2 wk	81[a]	2.2	Jordan et al. 2011
Nootkatone	Spray	Low	Dual, June	7.6 kg AI/ha	Woodland	2009	3 wk	100[a,b]	0	Jordan et al. 2011
Nootkatone	Spray	Low	Dual, June	7.6 kg AI/ha	Woodland	2009	4 wk	97[a,b]	0.4	Jordan et al. 2011
Nootkatone	Spray	Low	Dual, June	7.6 kg AI/ha	Woodland	2009	5 wk	96[a,b]	0.4	Jordan et al. 2011
Nootkatone	Spray	Low	Dual, June	7.6 kg AI/ha	Woodland	2009	6 wk	96[a,b]	0.2	Jordan et al. 2011
Nootkatone	Spray	High	Single, June	7.6 kg AI/ha	Woodland	Core, 2008	1 wk	98[a]	0.4	Dolan et al. 2009
Nootkatone	Spray	High	Single, June	7.6 kg AI/ha	Woodland	Core, 2008	2 wk	98[a]	0.4	Dolan et al. 2009
Nootkatone	Spray	High	Single, June	7.6 kg AI/ha	Woodland	Core, 2008	3 wk	100[a]	0	Dolan et al. 2009
Nootkatone	Spray	High	Single, June	7.6 kg AI/ha	Woodland	Core, 2008	4 wk	100[a]	0	Dolan et al. 2009
Nootkatone	Spray	High	Single, June	7.6 kg AI/ha	Woodland	Core, 2008	5 wk	98[a]	0.2	Dolan et al. 2009
Nootkatone	Spray	High	Single, June	7.6 kg AI/ha	Woodland	Core, 2008	6 wk	100[a]	0	Dolan et al. 2009
Nootkatone	Spray	High	Single, June	10.3 kg AI/ha	Residential	2008	~1 wk	100[a]	0	Bharadwaj et al. 2012
Nootkatone	Spray	High	Single, June	10.3 kg AI/ha	Residential	2008	~2 wk	49[a]	0.6	Bharadwaj et al. 2012

Natural product-based chemical acaricide used	Mode of application	Spray pressure	Application scheme	Amount or concentration of active ingredient (AI) applied	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Reference
								%reduction in TS	Abundance in TS	
Nootkatone	Spray	High	Single, June	10.3 kg AI/ha	Residential	2008	~3 wk	0[a]	4.2	Bharadwaj et al. 2012
Nootkatone	Spray	High	Single, June	10.3 kg AI/ha	Residential	2008	~4 wk	0[a]	3.1	Bharadwaj et al. 2012
Lignin-encapsulated nootkatone	Spray	High	Single, June	5.3 kg AI/ha	Residential	2009	~1 wk	100[a]	0	Bharadwaj et al. 2012
Lignin-encapsulated nootkatone	Spray	High	Single, June	5.3 kg AI/ha	Residential	2009	~2 wk	100[a]	0	Bharadwaj et al. 2012
Lignin-encapsulated nootkatone	Spray	High	Single, June	5.3 kg AI/ha	Residential	2009	~3 wk	100[a]	0	Bharadwaj et al. 2012
Lignin-encapsulated nootkatone	Spray	High	Single, June	5.3 kg AI/ha	Residential	2009	~4 wk	100[a]	0	Bharadwaj et al. 2012
Lignin-encapsulated nootkatone	Spray	High	Single, June	7.4 kg AI/ha	Residential	2010	~1 wk	67[a]	0.9	Bharadwaj et al. 2012
Lignin-encapsulated nootkatone	Spray	High	Single, June	7.4 kg AI/ha	Residential	2010	~2 wk	34[a]	0.9	Bharadwaj et al. 2012
Lignin-encapsulated nootkatone	Spray	High	Single, June	7.4 kg AI/ha	Residential	2010	~3 wk	13[a]	1.5	Bharadwaj et al. 2012
Lignin-encapsulated nootkatone	Spray	High	Single, June	7.4 kg AI/ha	Residential	2010	~4 wk	50[a]	0.6	Bharadwaj et al. 2012
Maillard-encapsulated nootkatone	Spray	High	Single, June	9.6 kg AI/ha	Residential	2010	~1 wk	62[a]	1.3	Bharadwaj et al. 2012
Maillard-encapsulated nootkatone	Spray	High	Single, June	9.6 kg AI/ha	Residential	2010	~2 wk	30[a]	1.2	Bharadwaj et al. 2012
Maillard-encapsulated nootkatone	Spray	High	Single, June	9.6 kg AI/ha	Residential	2010	~3 wk	11[a]	1.9	Bharadwaj et al. 2012
Maillard-encapsulated nootkatone	Spray	High	Single, June	9.6 kg AI/ha	Residential	2010	~4 wk	67[a]	0.5	Bharadwaj et al. 2012
Carvacrol										
Carvacrol	Spray	Low	Dual, June	7.6 kg AI/ha	Woodland	2010	1 wk	88[a]	1.8	Jordan et al. 2011

Natural product-based chemical acaricide used	Mode of application	Spray pressure	Application scheme	Amount or concentration of active ingredient (AI) applied	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Reference
								%reduction in TS	Abundance in TS	
Carvacrol	Spray	Low	Dual, June	7.6 kg AI/ha	Woodland	2010	2 wk	77[a]	3.2	Jordan et al. 2011
Carvacrol	Spray	Low	Dual, June	7.6 kg AI/ha	Woodland	2010	3 wk	94[a,b]	0.8	Jordan et al. 2011
Carvacrol	Spray	Low	Dual, June	7.6 kg AI/ha	Woodland	2010	4 wk	86[a,b]	1.0	Jordan et al. 2011
Carvacrol	Spray	Low	Dual, June	7.6 kg AI/ha	Woodland	2010	5 wk	93[a,b]	0.2	Jordan et al. 2011
Carvacrol	Spray	Low	Dual, June	7.6 kg AI/ha	Woodland	2010	6 wk	78[a,b]	1.0	Jordan et al. 2011
Carvacrol	Spray	Low	Single, May	39.4 kg AI/ha	Woodland	2007	1 wk	83[a]	2.0	Dolan et al. 2009
Carvacrol	Spray	Low	Single, May	39.4 kg AI/ha	Woodland	2007	2 wk	84[a]	2.0	Dolan et al. 2009
Carvacrol	Spray	Low	Single, May	39.4 kg AI/ha	Woodland	2007	3 wk	85[a]	2.2	Dolan et al. 2009
Carvacrol	Spray	Low	Single, May	39.4 kg AI/ha	Woodland	2007	4 wk	78[a]	2.4	Dolan et al. 2009
Garlic oil										
Garlic oil	Spray	High	Single, June	2.0 kg AI/ha	Residential	–	1 wk	37[a]	0.7	Bharadwaj et al. 2015
Garlic oil	Spray	High	Single, June	2.0 kg AI/ha	Residential	–	2 wk	59[a]	0.1	Bharadwaj et al. 2015
Garlic oil	Spray	High	Single, June	2.0 kg AI/ha	Residential	–	3 wk	47[a]	0.2	Bharadwaj et al. 2015
Combinations of plant oils										
Rosemary, peppermint, wintergreen	Spray	Low	Single, June	Lower	Woodland	2009	1 wk	37[a]	9.2	Jordan et al. 2011
Rosemary, peppermint, wintergreen	Spray	Low	Single, June	Lower	Woodland	2009	2 wk	10[a]	6.2	Jordan et al. 2011
Rosemary, peppermint, wintergreen	Spray	Low	Dual, June	Higher	Woodland	2010	1 wk	80[a]	2.6	Jordan et al. 2011

Natural product-based chemical acaricide used	Mode of application	Spray pressure	Application scheme	Amount or concentration of active ingredient (AI) applied	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Reference
								%reduction in TS	Abundance in TS	
Rosemary, peppermint, wintergreen	Spray	Low	Dual, June	Higher	Woodland	2010	2 wk	74[a]	3.0	Jordan et al. 2011
Rosemary, peppermint, wintergreen	Spray	Low	Dual, June	Higher	Woodland	2010	3 wk	95[a,b]	0.6	Jordan et al. 2011
Rosemary, peppermint, wintergreen	Spray	Low	Dual, June	Higher	Woodland	2010	4 wk	73[a,b]	1.6	Jordan et al. 2011
Rosemary, peppermint, wintergreen	Spray	Low	Dual, June	Higher	Woodland	2010	5 wk	67[a,b]	0.8	Jordan et al. 2011
Rosemary, peppermint, wintergreen	Spray	Low	Dual, June	Higher	Woodland	2010	6 wk	30[a,b]	2.6	Jordan et al. 2011
Rosemary, peppermint, wintergreen	Spray	High	Single, July	Lower	Woodland	–	1 wk	100[c]	0 / h	Rand et al. 2010
Rosemary, peppermint, wintergreen	Spray	High	Single, July	Lower	Woodland	–	2 wk	100[c]	0 / h	Rand et al. 2010
Rosemary, peppermint, wintergreen	Spray	High	Single, July	Lower	Woodland	–	1 wk	100[a]	0 / h	Elias et al. 2013
Rosemary, peppermint, wintergreen	Spray	High	Single, July	Lower	Woodland	–	2 wk	100[a]	0 / h	Elias et al. 2013
Rosemary, peppermint, wintergreen	Spray	High	Single, July	Lower	Woodland	–	4 wk	100[a]	0 / h	Elias et al. 2013

All studies were conducted in the northeastern United States.

[a]Calculated to account for pre- and posttreatment time point counts in both control and treatement areas, following Henderson and Tilton (1955) or Mount et al. (1976).

[b]After second application of the acaricide formulation.

[c]Calculated based on comparison of postintervention treatment value and postintervention control value.

Table 5

Percent reduction postintervention in abundance of *I. scapularis* nymphs, and end-point values for nymphal abundance, for single intervention methods based on application of biological fungal control agents to the environment

Fungal biological control agent used	Mode of application	Spray pressure	Application scheme	No. fungal spores applied per cm^2	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2)		Reference
								% reduction in TS	Abundance in TS	
Beauveria bassiana										
B. bassiana (ATCC 74040)	Spray	Low	Dual, June	2.2×10^3	Residential	2000	2–6 wk	38[c]	0.7	Stafford and Allan 2010
B. bassiana (GHA)	Spray	Low	Dual, June	9.9×10^5	Residential	2000	2–6 wk	55[c]	0.8	Stafford and Allan 2010
B. bassiana (ATCC 74040)	Spray	High	Dual, May–June	2.2×10^3	Residential	1999	2–6 wk	83[c]	0.3	Stafford and Allan 2010
B. bassiana (GHA)	Spray	High	Dual, June	9.9×10^5	Residential	1999	2–6 wk	74[c]	0.2	Stafford and Allan 2010
Metarhizium brunneum[a]										
M. brunneum (ESC1)	Spray	Low	Single, July	10^6	Woodland	Route 44A	1 wk	6[c]	~45[d]	Hornbostel et al. 2005a
M. brunneum (ESC1)	Spray	Low	Single, July	10^6	Woodland	Route 44A	3 wk	20[c]	~20[d]	Hornbostel et al. 2005a
M. brunneum (ESC1)	Spray	Low	Single, July	10^6	Woodland	Route 44A	4 wk	12[c]	~15[d]	Hornbostel et al. 2005a
M. brunneum (ESC1)	Spray	Low	Single, July	10^6	Woodland	Tompkins Farm	1 wk	20[c]	~10[d]	Hornbostel et al. 2005a
M. brunneum (ESC1)	Spray	Low	Single, July	10^6	Woodland	Tompkins Farm	3 wk	36[c]	~4[d]	Hornbostel et al. 2005a
M. brunneum (ESC1)	Spray	Low	Single, July	10^6	Woodland	Tompkins Farm	4 wk	26[c]	~2[d]	Hornbostel et al. 2005a
M. brunneum (F52)	Spray	High	Single, June–July[b]	1.3×10^6	Residential	–	3 wk	96[c]	0.1	Bharadwaj and Stafford 2010

Fungal biological control agent used	Mode of application	Spray pressure	Application scheme	No. fungal spores applied per cm^2	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2)		Reference
								% reduction in TS	Abundance in TS	
M. brunneum (F52)	Spray	High	Single, June–July[b]	1.3×10^6	Residential	–	5 wk	74[c]	0.3	Bharadwaj and Stafford 2010
M. brunneum (F52)	Spray	High	Single, June–July[b]	1.3×10^6	Residential	–	8 wk	78[c]	0.2	Bharadwaj and Stafford 2010
M. brunneum (F52)	Spray	High	Single, June–July[b]	3.2×10^5	Residential	–	3 wk	87[c]	0.2	Bharadwaj and Stafford 2010
M. brunneum (F52)	Spray	High	Single, June–July[b]	3.2×10^5	Residential	–	5 wk	53[c]	0.6	Bharadwaj and Stafford 2010
M. brunneum (F52)	Spray	High	Single, June–July[b]	3.2×10^5	Residential	–	8 wk	36[c]	0.6	Bharadwaj and Stafford 2010
M. brunneum (F52)	Spray	High	Dual, June–July	2.5×10^5	Lawn	–	2–6 wk	56[c]	0.2	Stafford and Allan 2010
M. brunneum (F52)	Spray	High	Dual, June–July	2.5×10^5	Wooded	–	2–6 wk	85[c]	0.2	Stafford and Allan 2010

All studies were conducted in the northeastern United States.

[a]Including varieties previously assigned to *Metarhizium anisopliae*.

[b]Listed as single rather than dual because a previous application 7 wk previously had very limited effect by the 5 wk time point.

[c]Calculated to account for pre- and posttreatment time point counts in both control and treatement areas, following Henderson and Tilton (1955) or Mount et al. (1976).

[d]Nymphal abundance estimated from data presented in graphs.

Table 6

Percent reduction postintervention in abundance of *I. scapularis* nymphs and *B. burgdorferi*-infected nymphs, and end-point values for these measures, for single intervention methods based on use of rodent-targeted topical acaricides

Rodent-targeted topical acaricide used	Start of intervention	Concentration of active ingredient (AI) applied	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Percent reduction relative to control sites (CS) and abundance of host-seeking infected nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Proportion of nymphs infected before and after intervention in treatment sites (TS), and percentage reduction in treatment sites relative to control sites (CS) after intervention			Reference
						% reduction in TS	Abundance in TS	% reduction in TS	Abundance in TS	Proportion infected nymphs in TS		% reduction in infection rate in TS relative to CS after intervention	
										Before intervention	After intervention		
Permethrin[a]	May 1986	7.4% w/w AI	Residential	–	1 yr (1987)	89[f]	7 / h	97[f]	0.62 / h	No data	0.09	72[f]	Mather et al. 1988
Permethrin[a]	May 1989	7.4% w/w AI	Residential	–	1 yr (1990)[c]	Increase[g]	0.50	Increase[g]	0.07	0.14[i]	0.15	Increase[g]	Stafford 1991b
Permethrin[a]	May 1989	7.4% w/w AI	Residential	–	2 yr (1991)[c]	7[g]	1.3	Increase[g]	0.20	0.14[i]	0.15	Increase[g]	Stafford 1992
Permethrin[a]	Aug. 1987	7.4% w/w AI	Residential	–	1 yr (1988)	Increase[f]	1.9	Increase[f]	0.32	No data	0.17	Increase[f]	Daniels et al. 1991
Permethrin[a]	Aug. 1987	7.4% w/w AI	Residential	–	2 yr (1989)	Increase[f]	1.1	Increase[f]	0.24	No data	0.22	8[f]	Daniels et al. 1991
Permethrin[a]	May 1988	7.4% w/w AI	Mixed R/W	PO'W site	1 yr (1989)[d]	22[g]	34 / h	27[f]	4.9 / h	No data[h]	0.15	14[f]	Ginsberg 2002
Permethrin[a]	May 1988	7.4% w/w AI	Woodland	FINS	1 yr (1989)[d]	Increase[g]	26 / h	74[g]	0.82 / h	0.19[i]	0.03	80[g]	Ginsberg 2002
Permethrin[a]	Aug. 1987	7.4% w/w AI	Woodland	–	2 yr (1989)[e]	100[f]	0 / h	No data	No data	No data	No data	No data	Deblinger and Rimmer 1991
Permethrin[a]	Aug. 1987	7.4% w/w AI	Woodland	–	3 yr (1990)[e]	97[f]	1.3 / h	No data	No data	No data	No data	No data	Deblinger and Rimmer 1991
Permethrin[a]	Aug. 1987	7.4% w/w AI	Woodland	–	1 yr (1988)	9[f]	8.0	Increase[f]	2.1	No data	0.26	Increase[f]	Daniels et al. 1991
Permethrin[a]	Aug. 1987	7.4% w/w AI	Woodland	–	2 yr (1989)	Increase[f]	14.7	Increase[f]	3.8	No data	0.26	Increase[f]	Daniels et al. 1991
Fipronil[b]	May 1999	0.75% AI	Residential	NPt site	1 yr (2000)	97[f]	1.8 / h	No data[h]	No data[h]	No data	No data[i]	No data[i]	Dolan et al. 2004
Fipronil[b]	May 1999	0.75% AI	Residential	NPt site	2 yr (2001)	96[f]	2.3 / h	No data[h]	No data[h]	No data	No data[i]	No data[i]	Dolan et al. 2004
Fipronil[b]	May 2000	0.75% AI	Residential	NA site	1 yr (2001)	62[f]	21 / hr	85[f]	1.7 / hr	0.24[i]	0.08	60[f]	Dolan et al. 2004

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Data also are presented for pre- and postintervention rates of *B. burgdorferi* infection in host-seeking nymphs in treatment sites and percentage reduction in infection rate in treatment sites relative to control sites after the intervention. All studies were conducted in the northeastern United States.

[a] Administered via treated cotton in Damminix tubes.

[b] Administered via treated wicks in rodent bait boxes.

[c] Presented nymphal abundance data are based on sampling conducted from June–July, infection rate data are based on nymphs collected from May–October.

[d] Re-calculated from raw data using data for nymphs from spring 1988 to estimate preintervention values and data for nymphs in spring 1989 to estimate postintervention values.

[e] Based on sampling dates on which both treatment and control sites were examined.

[f] Calculated based on comparison of postintervention treatment site value and postintervention control site value.

[g] Re-calculated from raw data presented in the study to account for pre- and posttreatment time point counts in both control and treatement areas, following Mount et al. (1976).

[h] Too few nymphs were collected to determine infection prevalence.

[i] Data for infection rate in host-seeking nymphs collected in the spring of the year when the intervention started reflects larval feeding in the summer and fall of the preceding year before the intervention started and therefore can be viewed as pretreatment data.

Table 7

Pre- and post intervention rates of *B. burgdorferi* infection in host-seeking *I. scapularis* nymphs in treatment sites and percent reduction in infection rate in treatment sites relative to control sites after the intervention for single intervention methods based on use of rodent-targeted antibiotics or vaccines

Type of intervention	Site	Start of intervention	Amount of active ingredient (AI) distributed	Setting	Timing of evaluation after start of intervention	Proportion of nymphs infected before and after intervention in treatment sites (TS), and percentage reduction in treatment sites relative to control sites (CS) after intervention				Reference
						Proportion infected nymphs in TS		% reduction in infection rate in TS relative to CS after intervention		
						Before intervention[c]	After intervention	Based on postintervention data only[d]	Based on pre- and postintervention data[e]	
Rodent-targeted oral antibiotic bait										
Doxycyline hyclate bait[a]	–	May 2007	500 mg / kg bait	Woodland	1 yr (2008)	0.37	0.019	93	94	Dolan et al. 2011
Doxycyline hyclate bait[a]	–	May 2007	500 mg / kg bait	Woodland	2 yr (2009)	0.37	0.015	92	93	Dolan et al. 2011
Rodent-targeted oral vaccine bait										
Vaccine with *E. coli* expressing OspA[b]	NY1 site	May 2007	200 mg / bait unit	Woodland	1 yr (2008)	0.53	0.55	Increase	8	Meirelles Richer et al. 2014
Vaccine with *E. coli* expressing OspA[b]	NY2 site	May 2008	200 mg / bait unit	Woodland	1 yr (2009)	0.38	0.30	30	67	Meirelles Richer et al. 2014
Vaccine with *E. coli* expressing OspA[b]	NY3 site	May 2009	200 mg / bait unit	Woodland	1 yr (2010)	0.47	0.31	Increase	5	Meirelles Richer et al. 2014
Vaccine with *E. coli* expressing OspA[b]	NY4 site	May 2009	200 mg / bait unit	Woodland	1 yr (2010)	0.58	0.34	Increase	16	Meirelles Richer et al. 2014
Vaccine with *E. coli* expressing OspA[b]	NY1 site	May 2007	200 mg / bait unit	Woodland	2 yr (2009)	0.53	0.45	Increase	68	Meirelles Richer et al. 2014
Vaccine with *E. coli* expressing OspA[b]	NY2 site	May 2008	200 mg / bait unit	Woodland	2 yr (2010)	0.38	0.32	Increase	49	Meirelles Richer et al. 2014

Type of intervention	Site	Start of intervention	Amount of active ingredient (AI) distributed	Setting	Timing of evaluation after start of intervention	Proportion of nymphs infected before and after intervention in treatment sites (TS), and percentage reduction in treatment sites relative to control sites (CS) after intervention				Reference
						Proportion infected nymphs in TS		% reduction in infection rate in TS relative to CS after intervention		
						Before intervention[c]	After intervention	Based on postintervention data only[d]	Based on pre- and postintervention data[e]	
Vaccine with *E. coli* expressing OspA[b]	NY3 site	May 2009	200 mg / bait unit	Woodland	2 yr (2011)	0.47	0.31	0	9	Meirelles Richer et al. 2014
Vaccine with *E. coli* expressing OspA[b]	NY4 site	May 2009	200 mg / bait unit	Woodland	2 yr (2011)	0.58	0.25	19	40	Meirelles Richer et al. 2014
Vaccine with *E. coli* expressing OspA[b]	NY1 site	May 2007	200 mg / bait unit	Woodland	3 yr (2010)	0.53	0.14	53	86	Meirelles Richer et al. 2014
Vaccine with *E. coli* expressing OspA[b]	NY2 site	May 2008	200 mg / bait unit	Woodland	3 yr (2011)	0.38	0.29	6	56	Meirelles Richer et al. 2014
Vaccine with *E. coli* expressing OspA[b]	NY1 site	May 2007	200 mg / bait unit	Woodland	4 yr (2011)	0.53	0.13	58	87	Meirelles Richer et al. 2014

All studies were conducted in the northeastern United States.

[a]Administered via rodent bait boxes (Protecta LP bait stations, Bell Laboratories, Inc.).

[b]Administered via rodent live traps.

[c]Data for infection rate in host-seeking nymphs collected in the spring of the year when the intervention started reflects larval feeding in the summer and fall of the preceding year before the intervention started and therefore can be viewed as pretreatment data.

[d]Re-calculated from raw data presented in the study by comparing postintervention treatment site value and postintervention control site value for the year in question.

[e]Re-calculated from raw data presented in the study to account for pre- and posttreatment time point counts in both control and treatement areas, following Mount et al. (1976).

Table 8

Percent reduction postintervention in abundance of *I. scapularis* nymphs and abundance of *B. burgdorferi*-infected nymphs, and end-point values for these measures, for single intervention methods based on deer reduction

Deer reduction threshold	Year deer density threshold achieved prior to peak fall activity period for tick adults	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after end-point was achieved	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2)		Percent reduction relative to control sites (CS) and abundance of host-seeking infected nymphs in treatment sites (TS) after intervention (per 100 m^2)		Percent reduction in infestation of rodents by nymphs (no. nymphs per animal) in treatment sites after intervention	Reference
					%reduction in TS	Abundance in TS	% reduction in TS	Abundance in TS		
<40 deer / km^2	2003	Bernards Township, NJ	Woods	3 yr (2005)	12[a]	2.1	No data	No data	No data	Jordan et al. 2007
<25 deer / km^2	1997	Bridgeport, CT	–	2 yr (1999)	No control site	3.3	No data	No data	No data	Stafford et al. 2003
<25 deer / km^2	1997	Bridgeport, CT	–	3 yr (2000)	No control site	2.4	No data	No data	No data	Stafford et al. 2003
<25 deer / km^2	1997	Bridgeport, CT	–	4 yr (2001)	No control site	2.5	No data	No data	No data	Stafford et al. 2003
<25 deer / km^2	1997	Bridgeport, CT	–	5 yr (2002)	No control site	0.7	No data	No data	No data	Stafford et al. 2003
<25 deer / km^2	1987	Crane Beach, MA	–	2 yr (1989)	No data	No data	No data	No data	78[b]	Deblinger et al. 1993
<25 deer / km^2	1987	Crane Beach, MA	–	3 yr (1990)	No data	No data	No data	No data	35[b]	Deblinger et al. 1993
<25 deer / km^2	1987	Crane Beach, MA	–	4 yr (1991)	No data	No data	No data	No data	41[b]	Deblinger et al. 1993
~5 deer / km^2	2002	Groton, CT	Lawn	2 yr (2004)	No control site	0.18	No control site	0.02	No data	Kilpatrick et al. 2014
~5 deer / km^2	2002	Groton, CT	Lawn	3 yr (2005)	No control site	0.35	No control site	0.04	No data	Kilpatrick et al. 2014
~5 deer / km^2	2002	Groton, CT	Lawn	4 yr (2006)	No control site	0.04	No control site	No data	No data	Kilpatrick et al. 2014
~5 deer / km^2	2002	Groton, CT	Woods	2 yr (2004)	No control site	0.67	No control site	0.08	No data	Kilpatrick et al. 2014

Deer reduction threshold	Year deer density threshold achieved prior to peak fall activity period for tick adults	Setting	Additional distinguishing year, site, or feature	Timing of evaluation after end-point was achieved	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2)		Percent reduction relative to control sites (CS) and abundance of host-seeking infected nymphs in treatment sites (TS) after intervention (per 100 m^2)		Percent reduction in infestation of rodents by nymphs (no. nymphs per animal) in treatment sites after intervention	Reference
					%reduction in TS	Abundance in TS	% reduction in TS	Abundance in TS		
~5 deer / km^2	2002	Groton, CT	Woods	3 yr (2005)	No control site	0.44	No control site	0.05	No data	Kilpatrick et al. 2014
~5 deer / km^2	2002	Groton, CT	Woods	4 yr (2006)	No control site	0.50	No control site	No data	No data	Kilpatrick et al. 2014
<2.5 deer / km^2	1984	Great Island, MA	–	2 yr (1986)	No data	No data	No data	No data	70[c]	Wilson et al. 1988
0 deer / km^2	1999	Monhegan Island, ME	–	3 yr (2002)	No data	No data	No data	No data	100[d]	Rand et al. 2004
0 deer / km^2	1999	Monhegan Island, ME	–	4 yr (2003)	No data	No data	No data	No data	100[d]	Rand et al. 2004

Data also are presented for reduction in infestation of rodents by *I. scapularis* nymphs in studies not presenting data for host-seeing nymphs. Studies with gradually decreasing deer density that lack a defined deer density threshold for some portion of the study are not included. All studies were conducted in the northeastern United States.

[a]Calculated to account for pre- and posttreatment time point counts in both control and treatement areas, following Mount et al. (1976).

[b]Calculated based on comparison of average preintervention values from 1983–1985 and yearly postintervention values from 1989–1991.

[c]Based on comparison of nymphal infestation on mice on Great Island as compared with a control island on which deer were not removed.

[d]Nymphs were consistently collected from rats on Monhegan Island from 1991–2001 but not from 2002–2003.

Table 9

Percent reduction postintervention in abundance of *I. scapularis* nymphs and abundance of *B. burgdorferi*-infected nymphs, and end-point values for these measures, for single intervention methods based on deer fencing

Type of deer fence	Additional distinguishing year, site, or feature	Setting	Size of deer exclosure area (ha)	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Percent reduction relative to control sites (CS) and abundance of host-seeking infected nymphs in treatment sites (TS) after intervention (per 100 m^2)		Reference
					% reduction in TS[a,b]	Abundance in TS	% reduction in TS	Abundance in TS	
Electric deer fence	Site B, 1992	Residential	7.4	2 yr	62	0.9	89[a,b]	0.02	Stafford 1993
Electric deer fence	Site A, 1991	Residential	3.2–3.6	>7 yr	47	1.9	35[a,b]	0.20	Stafford 1993
Electric deer fence	Site A, 1992	Residential	3.2–3.6	>7 yr	47	1.6	53[a,b]	0.18	Stafford 1993
Deer fence	All sites combined, 1991	Woodland	—-	>20 yr	83	0.5	87[a,b]	0.09	Daniels et al. 1993
Deer fence	Cemetery site, 1991	Woodland	6	>20 yr	83	0.4	Not shown[c]	Not shown[c]	Daniels et al. 1993
Deer fence	Far Archives site, 1991	Woodland	10	>20 yr	51	0.5	Not shown[c]	Not shown[c]	Daniels et al. 1993
Deer fence	Park Estate site, 1991	Woodland	101	>20 yr	92	0.1	Not shown[c]	Not shown[c]	Daniels et al. 1993
Deer fence	Near Archives site, 1991	Woodland	10	>20 yr	97	0.3	Not shown[c]	Not shown[c]	Daniels et al. 1993
Deer fence	Near Archives site, 1992	Woodland	10	>20 yr	79	4.0	No data	No data	Daniels and Fish 1995
Deer fence	Hudson Pines site, 1991	Woodland	24	>20 yr	Increase	1.0	Not shown[c]	Not shown[c]	Daniels et al. 1993
Deer fence	Hudson Pines site, 1992	Woodland	24	>20 yr	34	0.3	No data	No data	Daniels and Fish 1995
Deer fence	1998	Woodland	0.93–1.23	2 yr	40–45[d]	~40 / h[d]	No data	No data	Ginsberg et al. 2004
Deer fence	1999	Woodland	0.93–1.23	3 yr	Increase[d]	~60 / h[d]	No data	No data	Ginsberg et al. 2004
Deer fence	2000	Woodland	0.93–1.23	4 yr	40–45[d]	~40 / h[d]	No data	No data	Ginsberg et al. 2004

All studies were conducted in the northeastern United States.

[a]Calculated based on comparison of postintervention treatment value and postintervention control value.

[b]Based on comparison with areas outside of but close to the deer fence.

[c]Data not shown due to very small sample sizes for nymphs examined for presence of *B. burgdorferi* from treatment areas.

[d] Nymphal abundance estimated from data presented in a graph.

Table 10

Percent reduction postintervention in abundance of *I. scapularis* nymphs and abundance of *B. burgdorferi*-infected nymphs, and end-point values for these measures, for single intervention methods based on use of deer-targeted acaricides

Type of deer-targeted topical acaricide intervention	Acaricide used	Device density	Application scheme	Start of intervention	Primary setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Percent reduction relative to control sites (CS) and abundance of host-seeking infected nymphs in treatment sites (TS) after intervention (per 100 m^2)		Reference
								% reduction in TS	Abundance in TS	% reduction in TS	Abundance in TS	
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Variable	Mixed R/W	Meta-analysis NEATCP	2 yr	39[a]	No data	~35[d]	~0.15[d]	Brei et al. 2009, Gatewood Hoen et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Variable	Mixed R/W	Meta-analysis NEATCP	3 yr	48[a]	No data	~62[d]	~0.15[d]	Brei et al. 2009, Gatewood Hoen et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Variable	Mixed R/W	Meta-analysis NEATCP	4 yr	62[a]	No data	~50[d]	~0.09[d]	Brei et al. 2009, Gatewood Hoen et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Variable	Mixed R/W	Meta-analysis NEATCP	5 yr	61[a]	No data	~67[d]	~0.05[d]	Brei et al. 2009, Gatewood Hoen et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Variable	Mixed R/W	Meta-analysis NEATCP	6 yr	71[a]	No data	~68[d]	~0.07[d]	Brei et al. 2009, Gatewood Hoen et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Residential	Core area	4 yr (2001)	64[b]	No data	No data	No data	Daniels et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Residential	Core area	5 yr (2002)	55[b]	No data	No data	No data	Daniels et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Residential	Core area	6 yr (2003)	80[b]	No data	No data	No data	Daniels et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Residential	Core area	2 yr (1999)	46[c]	2.7	No data	No data	Stafford et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Residential	Core area	3 yr (2000)	50[c]	4.4	No data	No data	Stafford et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Residential	Core area	4 yr (2001)	63[c]	2.0	No data	No data	Stafford et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Residential	Core area	5 yr (2002)	65[c]	1.7	No data	No data	Stafford et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Residential	Core area	6 yr (2003)	70[c]	1.0	No data	No data	Stafford et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Mixed R/W	Core area	2 yr (1999)	~18[c,d]	~90 / h[d]	No data	No data	Miller et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Mixed R/W	Core area	3 yr (2000)	~3[c,d]	~180 / h[d]	No data	No data	Miller et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Mixed R/W	Core area	4 yr (2001)	~48[c,d]	~96 / h[d]	No data	No data	Miller et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Mixed R/W	Core area	5 yr (2002)	~53[c,d]	~90 / h[d]	No data	No data	Miller et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Mixed R/W	Core area	6 yr (2003)	~47[c,d]	~60 / h[d]	No data	No data	Miller et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Spring 1998	Mixed R/W	BARC, LR	4 yr (2002)	69–76[e]	No data	No data	No data	Carrol et al. 2009a

Type of deer-targeted topical acaricide intervention	Acaricide used	Device density	Application scheme	Start of intervention	Primary setting	Additional distinguishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2 unless specified as per h)		Percent reduction relative to control sites (CS) and abundance of host-seeking infected nymphs in treatment sites (TS) after intervention (per 100 m^2)		Reference
								% reduction in TS	Abundance in TS	% reduction in TS	Abundance in TS	
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Spring 1998	Mixed R/W	GI	4 yr (2002)	80[e]	No data	No data	No data	Carrol et al. 2009b
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Woodland	Core area	2 yr (1999)	59[c]	~2.4[d]	No data	No data	Schulze et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Woodland	Core area	3 yr (2000)	64[c]	~1.8[d]	No data	No data	Schulze et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Woodland	Core area	4 yr (2001)	61[c]	~2.6[d]	No data	No data	Schulze et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Woodland	Core area	5 yr (2002)	77[c]	~1.5[d]	No data	No data	Schulze et al. 2009
4-poster device	2% Amitraz	1/20–25 ha	Spring, fall	Fall 1997	Woodland	Core area	6 yr (2003)	80[c]	~1.1[d]	No data	No data	Schulze et al. 2009
4-poster device	10% Permethrin	Not clear	Spring, fall	Fall 1995	Woodland		2 yr (1997)	86[b]	No data	No data	No data	Solberg et al. 2003
4-poster device	10% Permethrin	Not clear	Spring, fall	Fall 1995	Woodland		3 yr (1998)	91[b]	No data	No data	No data	Solberg et al. 2003
4-poster device	Permethrin	~1/60 ha	Spring, fall	Fall 2007	Mixed R/W		Not clear	8[e]	No data	No data	No data	Grear et al. 2014

All studies were conducted in the northeastern United States.

[a]Calculated to account for pre- and posttreatment time point data in both control and treatement areas, as described by Brei et al. (2009).

[b]Calculated based on comparison of postintervention treatment value and postintervention control value.

[c]Calculated to account for pre- and posttreatment time point counts in both control and treatement areas, following Henderson and Tilton (1955) or Mount et al. (1976). Pretreatment baselines for nymphal abundance were estimated in 1998.

[d]Estimated from data presented in graphs.

[e]Calculated to account for pre- and posttreatment time point counts in both control and treatement areas, using generalized mixed linear models.

Table 11

Percent reduction postintervention in abundance of *I. scapularis* nymphs, and end-point values for nymphal abundance, for integrated tick and pathogen management approaches

Type of intervention	Mode of acaricide application	Spray pressure	Application scheme	Amount of active ingredient (AI) distributed, concentration of AI, or no. fungal spores applied per cm^2	Setting	Additional distin-guishing year, site, or feature	Timing of evaluation after start of intervention	Percent reduction relative to control sites (CS) and abundance of host-seeking nymphs in treatment sites (TS) after intervention (per 100 m^2)		Reference
								% re-duction in TS	Abun-dance in TS	
Deltamethrin in lawn-woods edge/Topical fipronil for rodents/Topical amitraz for deer	Granular/Wick/Roller	–	Single, May 2004 only/May–Aug., 2004–2005/ Spring and fall, from fall 2003 to sping 2007	150 g AI per ha/0.7% AI/2% AI	Residential	–	1 yr (2005)	87[b]	1.1	Schulze et al. 2007, 2008b
Deltamethrin in lawn-woods edge/Topical fipronil for rodents/Topical amitraz for deer	Granular/Wick/Roller	–	Single, May 2004 only/May–Aug., 2004–2005/ Spring and fall, from fall 2003 to sping 2007	150 g AI per ha/0.7% AI/2% AI	Residential	–	2 yr (2006)	94[b]	1.4	Schulze et al. 2007, 2008b
Deltamethrin in lawn-woods edge/Topical fipronil for rodents/Topical amitraz for deer	Granular/Wick/Roller	–	Single, May 2004 only/May–Aug., 2004–2005/ Spring and fall, from fall 2003 to sping 2007	150 g AI per ha/0.7% AI/2% AI	Residential	–	3 yr (2007)	86[b]	1.8	Schulze et al. 2007, 2008b
Beauveria bassiana (ATCC 74040)/Wood chip lawn edge barrier	Spray	High	Dual, May–June	2.2×10^3 spores	Residential	1999	2–6 wk	90[b]	0.2	Stafford & Allan 2010
Beauveria bassiana (GHA)/Wood chip lawn edge barrier	Spray	High	Dual, June	9.9×10^5 spores	Residential	1999	2–6 wk	89[b]	0.2	Stafford & Allan 2010
Beauveria bassiana (ATCC 74040)/Wood chip lawn edge barrier	Spray	High	Dual, June	2.2×10^3 spores	Residential	2000	2–6 wk	57[b]	0.5	Stafford & Allan 2010
Beauveria bassiana (GHA)/Wood chip lawn edge barrier	Spray	High	Dual, June	9.9×10^5 spores	Residential	2000	2–6 wk	55[b]	1.6	Stafford & Allan 2010
Nootkatone/*Metarhizium brunneum* (F52)[a]	Spray	High	Single, June	0.6 kg AI per ha/2.8×10^5 spores	Residential	–	1 wk	50[b]	0.4	Bharadwaj et al. 2012
Nootkatone/*Metarhizium brunneum* (F52)[a]	Spray	High	Single, June	0.6 kg AI per ha/2.8×10^5 spores	Residential	–	2 wk	Increase[b]	5.3	Bharadwaj et al. 2012
Nootkatone/*Metarhizium brunneum* (F52)[a]	Spray	High	Single, June	0.6 kg AI per ha/2.8×10^5 spores	Residential	–	3 wk	Increase[b]	1.7	Bharadwaj et al. 2012
Nootkatone/*Metarhizium brunneum* (F52)[a]	Spray	High	Single, June	0.6 kg AI per ha/2.8×10^5 spores	Residential	–	4 wk	Increase[b]	1.6	Bharadwaj et al. 2012

All studies were conducted in the northeastern United States.

[a]Including varieties previously assigned to *Metarhizium anisopliae*.

[b]Calculated to account for pre- and posttreatment time point counts in both control and treatement areas, following Henderson and Tilton (1955) or Mount et al. (1976).

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