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Issues

Review: Application of Tick Control Technologies for Blacklegged, Lone Star, and American Dog Ticks

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Abstract

Tick population control technologies have been studied for several decades but no method is successful in all situations. The success of each technology depends on tick species identity and abundance, host species identity and abundance, phenology of both ticks and hosts, geographic region, and a multitude of other factors. Here we review current technologies, presenting an overview of each and its effect on three common tick species in the eastern United States: blacklegged ticks (*Ixodes scapularis* (Say; Ixodida: Ixodidae)), lone star ticks (*Amblyomma americanum* (Linnaeus; Ixodida: Ixodidae)), and American dog ticks (*Dermacentor variabilis* (Say; Ixodida: Ixodidae)). Moreover, we assess the relative success among methods within the same season, as well as over successive years, in reducing tick populations by life stage. For each tick species and life stage, we present published findings, and in the absence of published studies, we hypothesize the most likely outcome based on tick life history. Integrated tick management over a specific time scale, using a variety of tick control technologies, will have the greatest effect on reducing tick abundance.

Key words: integrated tick management, tick control technologies, *Ixodes scapularis*, *Amblyomma americanum*, *Dermacentor variabilis*

Ticks and tick-borne diseases have been on the rise for the past couple of decades in the United States (Paddock et al. 2016). This has led to a demand by the general public for better tick control technologies, but a comprehensive method has yet to be developed (Eisen and Dolan 2016).

Tick control reviews have focused on summarizing a variety of intervention technologies and the measured outcome (Ostfeld et al. 2006, Eisen and Dolan 2016). This review is focused on the effectiveness of available tick control technologies on the three most commonly found tick species in the eastern portions of the United States. Recent research has reported the application of these technologies on the blacklegged tick (*Ixodes scapularis* (Say; Ixodida: Ixodidae)) because it is the vector for *Borrelia burgdorferi* (Johnson et al. mend. 1984; Baranton et al. 1992; Spirochaetales: Spirochaetaceae), the agent of the most common tick-borne disease in the United States, Lyme disease (Hinckley et al. 2014). However, the lone star tick (*Amblyomma americanum* (Linnaeus; Ixodida: Ixodidae)), which is the most prevalent tick in the southeastern United States, has been moving steadily northward (Childs and Paddock 2003). The American dog tick (*Dermacentor variabilis* (Say; Ixodida: Ixodidae)) has been found throughout the entire eastern United States for the past century (Sonenshine 1979). The lone star and American dog ticks both can carry different pathogens that can cause disease in humans and present very different challenges for tick population control (Randolph 2004).

The biggest difference among blacklegged, lone star, and American dog ticks is their phenology. While all three species are three-host, hard-bodied ticks, each life stage for each species has preferred hosts and seasonal timing.

Blacklegged tick larvae and nymphs are active during the late spring through summer, and adults are active in autumn and early spring (and winter in the southeastern United States) (Barbour and Fish 1993). Larvae prefer to feed on small mammals, reptiles, and birds, whereas nymphs feed on medium to large mammals and birds. Adults feed exclusively on large mammals.

Lone star tick adults and nymphs are active from late spring through mid-summer, and larvae are active in late summer through fall. All three life stages prefer to feed on large mammals, especially white-tailed deer (*Odocoileus virginianus* (Zimmerman; Artiodactyla: Cervidae)) (Childs and Paddock 2003).

American dog tick larvae and nymphs are active in the fall and spring while the adults are active during the summer. Larvae and nymphs feed on small mammals and birds, while the adults feed on medium and large mammals (Smart and Caccamise 1988). These differences in phenology and host-preference help explain the basis for many tick control technologies and why each species may respond differently to the same control measures.

Here we present an overview of each tick control technology (Table 1), followed by relevant published results for each tick species and life stage (Tables 2–4). If published results are unavailable, we hypothesize how each species and each life stage might be affected by control methods based on knowledge of tick biology, host preference, and phenology.

Table 1. Comparison of each control method and logistical limitations

Control method	Logistical concerns
Habitat modification	Proximity to houses
Controlled burns	Restricted areas
Synthetic acaricide	Restricted areas
Natural acaricide	Restricted areas
Fungal acaricide	Restricted areas
TickBot	Environmental setup required
Bait boxes	Potential increase in animal populations
Tick tubes	Potential increase in animal populations
Deer removal	Proximity to houses
Deer fence	Proximity to houses
4-poster device	Potential increase in animal populations

Habitat Modification

Ticks are susceptible to desiccation and spend much of their life in the leaf litter where there is high ground level humidity. Unmaintained forested and grassland areas all have a ground level layer of detritus made up of dead and decaying vegetation (Schlesinger 1977). Frequent mowing or removal of this vegetation through raking or other mechanical methods will reduce ground-level humidity, which will then reduce the survival of ticks that would be found in these areas (Clymer et al. 1970). If mulch is used, this can provide an area of lower humidity. One prescription for habitat modification is to install an approximately two-meter wide section of mulch between a path or maintained yard and a wooded or other heavily tick infested area (Stafford 2004, Piesman 2006).

Removal of leaf litter reduces lone star and blacklegged tick abundance. Because blacklegged ticks are the least mobile (Ginsberg

Table 2. Efficacy of each control method is described based on three time scales for blacklegged ticks

Blacklegged tick		Larvae			Nymph			Adult		
Control method	%	S	I	L	S	I	L	S	I	L
Habitat	>50%	*E*	—	—	39	—	—	*E*	—	—
Modification	<50%	—	*E*	*E*	—	*E*	*E*	—	*E*	*E*
Controlled	>50%	*E*	—	—	51	—	—	35, 55	35	—
Burns	<50%	—	*E*	*E*	30	*E*	*E*	—	55	35
Synthetic	>50%	37, 42, 44	—	—	1, 7, 18, 22, 34, 37, 38, 39, 40, 41, 42, 44, 46, 53	—	—	36, 44	—	—
Acaricide	<50%	—	*E*	*E*	—	*E*	*E*	—	*E*	*E*
Natural	>50%	1	—	—	1, 3, 15, 18, 26, 32, 34	—	—	32, 34	—	—
Acaricide	<50%	—	*E*	*E*	4, 26	*E*	*E*	—	*E*	*E*
Fungal	>50%	*E*	—	—	2, 53	—	—	*E*	—	—
Acaricide	<50%	—	*E*	*E*	24, 53	*E*	*E*	—	*E*	*E*
TickBot	>50%	*E*	—	—	19	—	—	*E*	—	—
	<50%	—	*E*	*E*	—	*E*	*E*	—	*E*	*E*
Bait	>50%	—	14	14, 15	—	14, 16	14, 15, 16, 43	—	16	16
Boxes	<50%	*E*	—	—	16	—	—	*E*	*E*	*E*
Tick	>50%	28, 29	29	*E*	28, 29	29	12	—	48	49
Tubes	<50%	—	8	—	—	8, 48	8, 49	*E*	—	—
Deer	>50%	—	—	13	—	—	13, 27	—	—	—
Removal	<50%	*E*	54	25, 56	*E*	54	25, 56	*E*	*E*	13, 25, 56
Deer	>50%	—	50	9, 10	—	—	9, 10, 50	—	—	9, 50
Fence	<50%	—	—	*E*	*E*	*E*	9, 20, 50	*E*	*E*	10, 50
4-Poster	>50%	—	—	47	—	—	5, 6, 11, 23, 31, 33, 43, 45, 47, 52	—	—	—
Device	<50%	*E*	*E*	11	*E*	*E*	17, 21, 52	*E*	47	11, 17, 47, 52

Short-term reduction is defined as relief within season, intermediate reduction is relief the following year, and long-term reduction would be relief for successive years. Reduction categories are defined as more or less than 50% relief from this tick population. If literature was not available then an expected outcome, *E*, based on the phenology of this life stage and species was determined. 1: Allan and Patrican (1995); 2: Bharadwaj and Stafford (2010); 3: Bharadwaj et al. (2012); 4: Bharadwaj et al. (2015); 5: Brei et al. (2009); 6: Carroll et al. (2009); 7: Curran etal. (1993); 8: Daniels et al. (1991); 9: Daniels et al. (1993); 10: Daniels and Fish (1995); 11: Daniels et al. (2009); 12: Deblinger and Rimmer (1991); 13: Deblinger et al. (1993); 14: Dolan et al. (2004); 15: Dolan et al. (2009); 16: Dolan et al. (2017); 17: Edwards et al. (2016); 18: Elias et al. (2013); 19: Gaff et al. (2015); 20: Ginsberg et al. (2004); 21: Grear et al. (2014); 22: Hinckley et al. (2016); 23: Hoen et al. (2009); 24: Hornbostel et al. (2005); 25: Jordan et al. (2007); 26: Jordan et al. (2011); 27: Kilpatrick et al. (2014); 28: Mather et al. (1987); 29: Mather et al. (1988); 30: Mather et al. (1993); 31: Miller et al. (2009); 32: Patrican and Allan (1995); 33: Pound et al. (2009); 34: Rand et al. (2010); 35: Rogers (1953); 36: Schulze et al. (1987); 37: Schulze et al. (1991); 38: Schulze et al. (1994); 39: Schulze et al. (1995); 40: Schulze et al. (2000); 41: Schulze et al. (2001); 42: Schulze et al. (2005); 43: Schulze et al. (2007); 44: Schulze et al. (2008); 45: Schulze et al. (2009); 46: Solberg et al. (1992); 47: Solberg et al. (2003); 48: Stafford (1991); 49: Stafford (1992); 50: Stafford (1993); 51: Stafford et al. (1998); 52: Stafford et al. (2009); 53: Stafford and Allan (2010); 54: Wilson et al. (1984); 55: Wilson (1986); 56: Wilson et al. (1988).

Table 3. Efficacy of each control method is described based on three time scales for lone star ticks

Lone star tick		Larvae			Nymph			Adult		
Control method	%	S	I	L	S	I	L	S	I	L
Habitat modification	>50%	12, 19	14, 19	12, 14	19	14, 19	12	14, 19	14, 19	14
	<50%	14	5		14	5	14	—	5	—
Controlled burns	>50%	1, 2, 6, 11, 15	11	—	2, 6, 11	11	—	6, 11	11	—
	<50%	—	2, 15	1, 2	15	2, 15	2	2, 15	2, 15	2
Synthetic acaricide	>50%	20	—	—	16, 18, 20, 23, 24, 25, 26	—	—	16, 18, 20, 23, 24, 26	—	—
	<50%	—	*E*	*E*	40	*E*	*E*	—	*E*	*E*
Natural acaricide	>50%	*E*	—	—	7, 17	—	—	*E*	—	—
	<50%	—	*E*	*E*	—	*E*	*E*	—	*E*	*E*
Fungal acaricide	>50%	*E*	—	—	*E*	—	—	*E*	—	—
	<50%	—	*E*	*E*	—	*E*	*E*	—	—	—
TickBot	>50%	*E*	—	—	9	—	—	9	—	—
	<50%	—	*E*	*E*	—	*E*	*E*	—	*E*	*E*
Bait boxes	>50%	—	—	—	—	—	—	—	—	—
	<50%	*E*	*E*	*E*	*E*	*E*	*E*	*E*	*E*	*E*
Tick tubes	>50%	—	—	—	—	—	—	—	—	—
	<50%	*E*	*E*	*E*	*E*	*E*	*E*	*E*	*E*	*E*
Deer removal	>50%	—	*E*	*E*	—	*E*	*E*	—	*E*	*E*
	<50%	*E*	—	—	*E*	—	—	*E*	—	—
Deer fence	>50%	—	3, 4	3, 4	—	—	4	—	—	4
	<50%	*E*	—	—	10	3, 4, 10	3, 10	10	3, 4, 10	3, 10
4-poster device	>50%	—	*E*	22	21	—	—	21	*E*	13
	<50%	*E*	—	8, 13	—	—	8, 13	—	—	8

Short-term reduction is defined as relief within season, intermediate reduction is relief the following year, and long-term reduction would be relief for successive years. Reduction categories are defined as more or less than 50% relief from this tick population. If literature was not available then an expected outcome, *E*, based on the phenology of this life stage and species was determined. 1: Allan (2009); 2: Barnard (1986); 3: Bloemer et al. (1986); 4: Bloemer et al. (1990); 5: Clymer et al. (1970); 6: Davidson et al. (1994); 7: Dolan et al. (2009); 8: Edwards et al. (2016); 9: Gaff et al. (2015); 10: Ginsberg et al. (2002); 11: Gleim et al. (2014); 12: Hair and Howell (1970); 13: Harmon et al. (2011); 14: Hoch et al. (1971a); 15: Hoch et al. (1972); 16: Hughes et al. (2014); 17: Jordan et al. (2011); 18: Mount et al. (1976); 19: Mount (1981); 20: Mount (1984); 21: Pound et al. (2000); 22: Pound et al. (2009); 23: Roberts et al. (1980); 24: Sardelis et al. (1989); 25: Schulze et al. (2001); 26: Solberg et al. (1992).

and Ewing 1989) and the least desiccation tolerant (Goodman et al. 2005), habitat modification has a short-lived but marked reduction of 73–100% on the abundance of both nymphal and larval stages (Schulze et al. 1995). Lone star ticks are known to move ten meters in search of a carbon dioxide source (Falco and Fish 1991), which may limit the success of leaf litter removal. By clearing vegetation, lone star tick abundance for all life stages has been reduced by 40–50% for at least 2 mo (Clymer et al. 1970). In one case, clearing vegetation reduced the abundance of larval lone star ticks by 93% four weeks later and 72% two years later (Hair and Howell 1970). In this same study, 2 yr following vegetation removal, nymph and adult lone star ticks were also suppressed by 53 and 75%, respectively. In fact, clearing vegetation resulted in less than 50% survival of all life stages of lone star ticks within the first year followed by a reduction in abundance of 47–85% for larvae, 29–39% for nymphs, and 52–62% for adults in the following 3 yr (Hoch et al. 1971b). After intensive habitat modification by removing some over story, all understory, and mowing nearby areas for consecutive years, abundance of lone star ticks of all life stages was reduced on average overall by 76–93% (Mount 1981). Herbicides have also been used solely or together with vegetation clearing and have reported similar results for lone star tick reduction in abundance (Clymer et al. 1970, Hair and Howell 1970, Hoch et al. 1971a, Barnard 1986).

American dog ticks are not as mobile as other ticks (Sonenshine et al. 1966, Falco and Fish 1991) but are more tolerant of desiccation (Goodman et al. 2005). No studies were found that specifically targeted habitat modification to reduce American dog ticks, but a study of a related species, *Dermacentor andersoni* (Stiles; Ixodida: Ixodidae), found no effect from herbicide treatment (Wilkinson 1977).

Leaf litter removal and installation of a mulch barrier can provide an immediate reduction in risk of tick encounter (Clymer et al. 1970). Leaf litter removal is labor-intensive and requires continual maintenance. There is no known long-term method to treat large areas effectively. Additionally, removal of leaf litter can adversely affect other arthropods that rely on such habitat, including many pollinators (Ginsberg et al. 2017).

Controlled Burns

Historically, many forested habitats had natural cycles of burning that allowed the ecosystem to release carbon from woody vegetation, to germinate fire-stimulated seeds, and to reset succession (Rego et al. 1991, Sparks et al. 1998, Kirkman et al. 2001). Many areas are subjected to controlled burns to mimic natural fire frequencies and to prevent destructive fires that result from excessive fuel build-up. There are numerous logistical challenges to prescribed burning, including the potential for loss of control of the fire and conservative burn prescriptions in suburban areas. Ticks present within these environments can be directly affected by the initial fire through exposure to the intense temperatures or indirectly by the effect the burn has on vegetation and hosts. Controlled burns have been tested as a way to manage tick populations for lone star, American dog, and blacklegged ticks.

The use of fire as a control for ticks has been used most extensively for lone star ticks with idiosyncratic results for all life stages. Burning an area can reduce the lone star tick abundance within the same year

Table 4. Efficacy of each control method is described based on three time scales for American dog ticks

American dog tick		Larvae			Nymph			Adult		
Control method	%	S	I	L	S	I	L	S	I	L
Habitat modification	>50%	—	—	—	—	—	—	*E*	—	—
	<50%	*E*	*E*	*E*	*E*	*E*	*E*	—	*E*	*E*
Controlled burns	>50%	—	—	—	—	—	—	*E*	3	—
	<50%	*E*	*E*	*E*	*E*	*E*	*E*	—	*E*	*E*
Synthetic acaricide	>50%	—	—	—	—	—	—	4	—	—
	<50%	*E*	*E*	*E*	*E*	*E*	*E*	—	*E*	*E*
Natural acaricide	>50%	—	—	—	—	—	—	*E*	—	—
	<50%	*E*	*E*	*E*	*E*	*E*	*E*	—	—	—
Fungal acaricide	>50%	—	—	—	—	—	—	*E*	—	—
	<50%	*E*	*E*	*E*	—	*E*	*E*	—	*E*	*E*
TickBot	>50%	—	—	—	—	—	—	*E*	—	—
	<50%	*E*	*E*	*E*	*E*	*E*	*E*	—	*E*	*E*
Bait boxes	>50%	1	*E*	*E*	1	*E*	*E*	—	*E*	*E*
	<50%	—	—	—	—	—	—	*E*	—	—
Tick tubes	>50%	2	*E*	*E*	2	*E*	*E*	—	*E*	*E*
	<50%	—	—	—	—	—	—	*E*	—	—
Deer removal	>50%	—	—	—	—	—	—	—	—	—
	<50%	*E*	*E*	*E*	*E*	*E*	*E*	*E*	*E*	*E*
Deer fence	>50%	—	—	—	—	—	—	—	—	—
	<50%	*E*	*E*	*E*	*E*	*E*	*E*	*E*	*E*	*E*
4-poster device	>50%	—	—	—	—	—	—	—	—	—
	<50%	*E*	*E*	*E*	*E*	*E*	*E*	*E*	*E*	*E*

Short-term reduction is defined as relief within season, intermediate reduction is relief the following year, and long-term reduction would be relief for successive years. Reduction categories are defined as more or less than 50% relief from this tick population. If literature was not available then an expected outcome, *E*, based on the phenology of this life stage and species was determined. 1: Sonenshine and Haines (1985); 2: Mather et al. (1987); 3: Smith et al. (1946); 4: White et al. (1981).

as the burn for larvae (Hoch et al. 1972, Barnard 1986, Davidson et al. 1994, Cully 1999). The results for reduction in nymphs and adults are not consistent with reports of reduction of nymph abundance (Barnard 1986, Davidson et al. 1994) and adult abundance (Davidson et al. 1994, Cully 1999). Within only 2 yr after a burn, lone star tick abundance returned to pre-burn levels or even increased in some cases by more than six times the density in unburned areas (Barnard 1986, Davidson et al. 1994, Cully 1999, Allan 2009).

Less research has been done on American dog and blacklegged ticks using burning for control, and for these species the results are also variable. Fire can suppress the abundance of American dog ticks within the same year as a fire (Smith et al. 1946), but no published studies exist to the best of our knowledge. Similar to the lone star tick results, abundance can be reduced within the same season as a fire for blacklegged nymphs (Mather et al. 1993, Stafford et al. 1998) and adults (Rogers 1953, Wilson 1986), but all abundances returned to pre-burn levels within 2 yr.

Overall, most studies suggest that any reduction in tick numbers will be short-lived and will return to pre-fire or even higher densities within a year or two. Because nymphs and larvae of both blacklegged ticks and American dog ticks feed regularly on small mammals, these taxa tend to quest lower in the vegetation, allowing them to potentially avoid direct contact with the fire compared with lone star ticks. Annual burns could result in lower abundance of all three species (Gleim et al. 2014), but there are few areas that would tolerate annual burns. The logistical challenges of controlled burns preclude this option for many areas, especially those near residential areas.

Broadcast Acaricides

In an effort to kill ticks a variety of acaricides have been used including synthetic chemicals, naturally-occurring chemicals, and fungal agents. Many factors influence the effectiveness of these agents including the intensity of the spraying, the length of time the acaricides remain effective, and the weather (Eisen and Dolan 2016). Additionally, there are many regulatory and other factors to consider as acaricides are not as targeted as the name may imply and will often adversely affect other arthropods including beneficial insects such as honey bees (*Apis* spp. (Linnaeus; Hymenoptera: Apidae)).

Synthetic Acaricides

Area-wide application of synthetic acaricides includes the use of sprays or granular preparations that vary in frequency of application, season targeted for treatment, or intensity of application. During the 1950s–1980s, application of sprays and granular preparations were successful in reducing lone star and blacklegged ticks of different life stages within the same (McDuffie et al. 1950; Mount et al. 1968, 1976; Hair and Howell 1970; Roberts et al. 1980; Mount 1984; Schulze et al. 1987; Sardelis et al. 1989; Curran et al. 1993; Piesman and Gray 1994). Many of the early studies focused on organophosphates, which are no longer available for residential use. Currently available acaricides include pyrethroid pesticides and carbamates, but even these are restricted for use near wetlands, open water, or plants intended for human consumption (Eisen and Dolan 2016). Single application synthetic acaricides have been shown to reduce abundance of blacklegged nymphs by 64–100% for at least 6 wk (Solberg et al. 1992; Curran et al. 1993; Allan and Patrican 1995; Schulze et al. 1991, 1994, 1995, 2000, 2001, 2005, 2008; Rand et al. 2010; Stafford and Allan 2010; Elias et al. 2013). Synthetic acaricides that work for blacklegged nymphs have had mixed results for reductions of lone star ticks (Solberg et al. 1992; Schulze et al. 2000, 2001). The use of synthetic acaricides on American dog ticks showed an 82% reduction after a single spray, 95% after two sprays, and 96% reduction after three sprays (White et al. 1981). Although a reduction in questing ticks was noted, it did not directly relate to decreased risk of tick encounters or reduced incidence of tick-borne pathogens (Hinckley et al. 2016). To the best of our knowledge, no studies demonstrate reductions in tick populations in subsequent years.

Natural Acaricides

As an alternative to synthetic chemicals, acaricides derived from naturally occurring substances, termed 'natural acaricides', have been developed, e.g., nootkatone (Panella et al. 2005). These acaricides have more societal acceptance and compliance for residential use (Gould et al. 2008). Results of broadcast application of these natural acaricides are similar to the synthetics but reduction of tick abundance lasts for shorter period of time. Within 2 wk of treatment, reduction of blacklegged nymph numbers typically varies from 57 to 100% but effectiveness is considerably reduced in subsequent weeks (Allan and Patrican 1995; Patrican and Allan 1995; Dolan et al. 2009; Rand et al. 2010; Jordan et al. 2011; Bharadwaj et al. 2012, 2015; Elias et al. 2013). Nootkatone can suppress nymph lone star and blacklegged ticks from 91 to 96% after 35–42 d (Jordan et al. 2011). In a lab setting, nootkatone was lethal to American dog ticks (Flor-Weiler et al. 2011). These natural acaricides do not persist as long in the environment reducing the ability to control ticks for long periods of time and by applying chemicals to the environment, natural acaricides can kill other arthropods including non-target species (Elias et al. 2013, Ginsberg et al. 2017).

Fungal Acaricides

In an effort to create an acaricide that targets ticks in the leaf litter, entomopathogenic fungal biological control has been used. Both *Beauveria bassiana* (Bals.-Criv.; Hypocreales: Clavicipitaceae) strains and *Metarbizium brunneum* (Petch; Hypocreales: Clavicipitaceae) strains have been studied in a field setting for controlling blacklegged ticks (Hornbostel et al. 2005, Bharadwaj and Stafford 2010, Stafford and Allan 2010). In the field, application of these fungi reduced blacklegged tick nymphs within the same year with varying success from a low of 12–26% (Hornbostel et al. 2005) to a high of 87–96% (Bharadwaj and Stafford 2010). *M. brunneum* and *B. bassiana* cause mortality in many species of ticks including lone star and American dog ticks in a lab setting but need further field studies (Kirkland et al. 2004a,b). The entomopathogenic fungi have not been reported to have major affects on other beneficial insects, but caution with application to avoid these species should still be taken (Ginsberg et al. 2017, Zimmermann 2007a,b).

Furthermore, within the United States, application of the entomopathogenic fungi is still restricted when near open water or wetlands (Environmental Protection Agency 2011). Success of fungal acaricides is sensitive to how and when they are applied to the environment as well as environmental conditions like humidity or temperature (Zimmermann 2007a,b).

Little research has been conducted to measure the effect of modern acaricides on lone star or American dog ticks in field settings. While it might be expected that these species would experience similar reductions to the blacklegged ticks, the variation in reported lab mortalities from fungal acaricides (Kirkland et al. 2004a,b) indicates that more research is needed.

TickBot

Questing ticks use movement and carbon dioxide to find a host. Adult American dog ticks, lone star nymphs and adults, and all life stages of blacklegged ticks will move horizontally towards these cues (Goddard 1992, Sonenshine 1993). TickBot is a semi-autonomous robot that follows a prescribed path and lures questing ticks to an acaricide impregnated cloth through movement and release of carbon dioxide. Ticks that are in the proximity of the cloth as the robot circulates on its path will come in contact with the acaricide and die (Gaff et al. 2015).

TickBot provided relief from lone star ticks for 24 h within a given perimeter (Gaff et al. 2015). TickBot is expected to be effective on ticks that are questing and come in contact with the cloth. Lone star nymphs and adults are aggressive and will move toward a 'host' (Childs and Paddock 2003), and therefore TickBot is expected to be effective on these life stages. Lone star larvae and all stages of blacklegged and American dog ticks are ambush questing ticks (Goddard 1992, Sonenshine 1993) and likely to move shorter distances (Falco and Fish 1992, Mays et al. 2016) towards the TickBot, resulting in a smaller protected area. If any of these ticks are questing along the path of the TickBot, they will be killed upon contact with the permethrin treated cloth (Schreck et al. 1982, 1986; Mount and Snoddy 1983). Another potential issue is that American dog tick nymphs and larvae are unlikely to be affected by this treatment because they remain under the leaf litter protected from the treated cloth.

Bait Boxes

Juveniles of blacklegged and American dog ticks generally feed upon smaller hosts such as small mammals like rodents and shrews (Sonenshine 1993). The white-footed mouse (*Peromyscus leucopus*) (Rafinesque; Rodentia: Cricetidae) has been implicated as supplying a reservoir for pathogens such as *B. burgdorferi*, the causative agent of Lyme disease (Ostfeld 2010). Targeting rodents to remove ticks from them and interrupting this part of the life cycle could, in turn, reduce tick-borne pathogens harbored by ticks as well as possibly reducing the tick populations themselves. Bait boxes are designed to remove ticks from rodents (Sonenshine and Haines 1985, Dolan et al. 2004). These are small plastic enclosed boxes fitted with bait for rodents as well as a wick to apply an acaricide to the rodents as they enter or exit the box. The design of these control devices has been modified to more effectively target the appropriate hosts and reduce damage from non-target hosts (Dolan et al. 2017). Commercially available bait boxes include the Maxforce TMS Bait Boxes. The bait boxes are targeted towards rodents and thus only work on those species of ticks that feed upon rodents. Nymphs and larvae of American dog and blacklegged ticks may be reduced by this intervention (Sonenshine and Haines 1985), allowing two opportunities (one per life stage) to disrupt the phenology of these tick species. It is unlikely that this control method would have any effect on lone star tick populations since lone star ticks do not feed on rodents (Zimmerman et al. 1987).

A bait box that incorporated dust or oil to treat rodents reduced nymphal and larval American dog ticks by 81.2 and 97.8% per host, respectively, relative to control conditions (Sonenshine and Haines 1985). Bait boxes were used at residential properties for 3 yr and found that larval and nymphal ticks on hosts were reduced by 84 and 68%, respectively. Questing adult blacklegged ticks were reduced by 77% and questing nymph blacklegged ticks were reduced by 68% (Dolan et al. 2004). This finding was repeated by Dolan et al. (2017) with a similar reduction of blacklegged ticks on and off host. Using both bait boxes and 4-poster control methods (described described in the section 4-Poster Device), questing nymphs, larvae, and adults were reduced by 58.5, 24.8, and 77.8%, respectively, within the same year (Schulze et al. 2007).

One logistical concern regarding bait boxes is the potential increase in rodent survival and reproduction as a function of the food provided in the control mechanism. Additionally, the acaricide would reduce all ectoparasites on the rodents that could further improve the survival of the treated animals (Ostfeld et al. 2006).

Future bait boxes may include the ability to treat rodents with antibiotics or vaccines rather than acaricide (Dolan et al. 2017). Rodents are often food-limited, and any increase in the rodent food source could result in a population increase that offsets any reduction in tick populations (Boutin 1990). Worse, the additional availability of food from the bait boxes could result in additional hosts for ticks in subsequent years.

Tick Tubes

As mentioned above, rodents play a large role as hosts for some ticks and reservoirs for many tick-borne illnesses. Tick tubes are another tick control technology that targets immature ticks that feed on rodents. The method provides acaricide-treated cotton for rodents to use in their nests. This, in turn, reduces ectoparasites on the rodents and in their nests. Tick tubes are expected to control nymphs and larvae of blacklegged and American dog ticks. However, as with bait boxes, lone stars would not be affected by this intervention since they do not feed on rodents (Zimmerman et al. 1987).

Studies on the effectiveness of tick tubes have been equivocal with some investigators detecting no reduction in ticks on rodents and in the nearby environment, while others have found a dramatic reduction. After continuous treatment with tick tubes, blacklegged ticks on white-footed mice showed no significant decrease in tick infestations nor did blacklegged ticks found questing in the same area for 2 yr in New York (Daniels et al. 1991) and 3 yr in Connecticut (Stafford 1991, 1992). In Massachusetts, treatment with tick tubes showed a reduction of blacklegged and American dog tick larvae and nymphs with 28% of white-footed mice found infested in the treated area versus 99% infested in control areas (Mather et al. 1987). In two similar studies, tick tubes used seasonally showed reduction of tick infestation on rodents to essentially zero for two seasons (Mather et al. 1988, Deblinger and Rimmer 1991).

While this control measure does not provide an additional food source as bait boxes would, it does still change the exposure of the rodents to ectoparasites. By providing nesting materials and reducing parasite load on these rodents, tick tubes may increase the survival of hosts. Increased survival could result in unintended consequences if there are more hosts present to be parasitized by ticks. There is also a need for research to better understand why the results on effectiveness are so disparate.

Deer Removal

White-tailed deer are considered to be the principal host for several adult tick species (Patrick and Hair 1978; Bloemer et al. 1986, 1988; Barbour and Fish 1993). Throughout the eastern United States, deer are becoming a nuisance species to humans and deer overpopulation results in increasing tick populations (Rand et al. 2003). Deer are the dominant host of all life stages of lone star ticks and for adults of blacklegged ticks. American dog ticks are not known to feed on deer as frequently and would not be affected as much by this intervention as lone star ticks or blacklegged ticks (Anderson and Magnarelli 1980, Kollars et al. 2000).

Reduction in deer populations produced varying results depending on how much abundance was reduced and the length of time since deer removals. While some studies have shown reductions in blacklegged tick larvae and nymphs in the same year (Wilson et al. 1984), other studies have shown no change or increases (Deblinger et al. 1993, Rand et al. 2004). Similarly, there were conflicted outcomes in subsequent years with reported increases in blacklegged nymph abundance in year 2 (Jordan et al. 2007), no changes in years 2 and 3 (Deblinger et al. 1993), or reduction by year 3 (Wilson et al. 1988). Even removal of deer to extinction or near extinction was not able to demonstrate elimination of blacklegged tick populations (Wilson et al. 1988, Deblinger et al. 1993, Rand et al. 2004, Kilpatrick et al. 2014). To the best of our knowledge, no deer removal studies have focused on control of the lone star tick. Given that lone star ticks feed predominantly, but not exclusively, on white-tailed deer, the outcomes would likely be conflicting as with the blacklegged tick population studies.

While deer play an important role in the blacklegged tick population, there are additional hosts that can sustain a blacklegged tick population in the absence of deer. Likewise, the increase in ticks during the first years after the reduction in deer populations serves as a good reminder that interventions can have unintended consequences. Finally, while removal of deer would be anticipated to result in reduction in lone star tick populations and minimal if any change in dog tick populations, little work has been done to explore these dynamics.

Deer Fence

To combat public resistance to culling of deer, fencing has been used to exclude deer and thereby reduce host availability. Although deer are excluded from fenced off areas, other potential hosts such as white-footed mice (*P. leucopus*), raccoons (*Procyon lotor*) (Linnaeus; Carnivora: Procyonidae), and opossums (*Didelphis virginiana*) (Kerr; Didelphimorphia: Didelphidae) can maintain tick populations (Sonenshine 1993). Lone star ticks of all life stages feed on deer and would likely be the most affected by this intervention (Childs and Paddock 2003). Blacklegged ticks also frequently feed on deer and may show some reduction, but American dog ticks would likely remain unaffected as they prefer medium-sized mammals and rodents (Anderson and Magnarelli 1980, Kollars et al. 2000).

In a long-term study, deer were excluded from an area in New York for more than 25 yr. These exclosures showed reduced blacklegged nymphal and larval burden on small- and medium-sized mammals (Daniels and Fish 1995). Similarly, questing blacklegged tick abundance, at the same study sites, was reduced by 90% fewer larvae and 83% fewer nymphs compared with the areas without exclosures (Daniels et al. 1993). Exclosures present for a shorter period of time showed variation in blacklegged nymph abundance in an exclosure area during the first 4 yr (Ginsberg et al. 2002, 2004). Deer exclosures were successful in reducing lone star larvae in treated plots, but have mixed results for adults and nymphs (Bloemer et al. 1986, 1990). The exclosures have resulted in American dog ticks becoming the numerically dominant species (Zimmerman et al. 1987).

Wide-scale use of deer exclosures is not practicable and may have other ecological implications such as inhibiting successional development. Additionally, while white-tailed deer play a large role in the life history of blacklegged and lone star ticks, the shift to the dog tick as a numerically dominant species in the exclosure area for at least one study could simply result in a shift of species rather than a reduction in tick encounters for the treated areas.

4-Poster Device

If removing or excluding the host is not possible, treating deer directly with an acaricide is an alternative. Deer have been fitted with acaricide impregnated collars or lured to ivermectin bait to reduce lone star tick populations (Pound et al. 1996, 2012), but these methods can be challenging unless the majority of the host population is accessible for treatment. While previous work found reductions in the blacklegged tick population using self-applied acaricide

(Sonenshine et al. 1996), the most common device today is the 4-poster method. The 4-poster devices apply an acaricide to the deer via rollers to the head, neck, and ears as the deer feed on corn or other food provided as bait (Pound et al. 2000). Lone star and blacklegged ticks are frequently found feeding on the ears and head, and are killed when the animal self-applies this treatment (Bloemer et al. 1988, Schmidtmann et al. 1998). The treatment can last for approximately a month and as a result can protect the deer beyond the initial application for subsequent tick encounters (Pound et al. 2000).

The 4-poster devices have been heavily studied for blacklegged tick reduction in successive years. Lone star ticks preferentially feed on larger animals such as deer, and these ticks can be found on deer at all life stages (Childs and Paddock 2003). However, lone star ticks can develop resistance to certain acaricides, which leads to varying efficacy results (Grear et al. 2014). American dog ticks are expected to have limited, if any, reduction in population density by 4-poster intervention as deer are not a major host of this species (Anderson and Magnarelli 1980, Kollars et al. 2000).

Meta-analysis of the United States Department of Agriculture Northeast area-wide tick control project by Brei et al. (2009) found that, by the sixth year of intervention with 4-poster devices, blacklegged ticks had been reduced by 71% at treatment sites. Additional studies have found reduction in blacklegged tick populations in areas where the 4-poster was deployed (Solberg et al. 2003, Carroll et al. 2009, Daniels et al. 2009, Hoen et al. 2009, Miller et al. 2009, Pound et al. 2009, Stafford et al. 2009, Grear et al. 2014). Other studies focused on the lone star tick found similar results with dramatic decreases in all life stages (Schulze et al. 2007, Carroll et al. 2009, Pound et al. 2009, Harmon et al. 2011). In contrast, a study in Virginia found no significant difference between blacklegged or lone star tick numbers found on deer between control and treatment sites (Edwards et al. 2016).

The amount of use of 4-poster was also noted to have negative effects on the vegetation near the 4-poster with high levels of deer browse, soil disruption, and damage to ground cover. In addition, 4-poster devices can also be sites for wildlife to gather with the potential to transmit pathogens, allowing them to spread between both targeted and non-targeted animals, e.g., chronic wasting disease (Brown and Cooper 2006). Finally, non-target wildlife have also been a nuisance in areas where the 4-poster devices are implemented, and this has resulted in restrictions on the use of these devices in some areas (Edwards et al. 2016).

Conclusions

To manage tick populations, several technologies have been developed, but no single technology has been able to control all species at all life stages. While some control measures can yield immediate results such as acaricides or the TickBot, other technologies may take years to reach full efficacy (i.e., 4-poster, or tick tubes). Knowing the phenology of local species can facilitate more effective timing of treatment. Future field research is needed in integrated tick management to use novel methods that account for varying phenologies, the type of habitat, and the corresponding relationship with ticks and tick-borne diseases.

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