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Integrated Pest Management in Controlling Ticks and Tick-Associated Diseases

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Abstract

The increasing prevalence of Lyme disease and the emergence of other tick-associated human diseases in the United States have become a major public health concern. A wide variety of personal protection measures and tick control strategies have been used or investigated to reduce contact between ticks and humans, reduce tick abundance, or lower the prevalence of tick-borne agents in the ticks. These methods have generally been applied or evaluated as single interventions and other than some early computer model simulations, studies applying integrated tick management approaches are few. In this paper, we review surveyed human behaviors and risks for exposure to ticks, concepts pertinent to integrated pest management for ticks, simulation models, various tick control strategies, integrated tick management studies, and highlight what is needed going forward. Increased education and communication between physicians and veterinarians is essential to address tick-associated diseases in a 'one health' approach and unify the animal and human branches of medicine to identify, treat, and implement preventive measures. Novel simulation models using more recent empirical data on tick population dynamics, hosts, efficacy of various combinations of interventions, human exposure elements, and utilization of personal and environmental measures will help us better understand the interactions of integrated strategies for tick population management. Many questions remain related to the ecology of ticks and tick-borne pathogens, observed and modeled efficacy of various integrated interventions, human behavior and exposure to tick bite and disease risk, comparative cost of interventions, and the acceptance and use of prevention and tick control tools.

Key words: Integrated tick management, *Ixodes scapularis*, Lyme disease, tick control

The increasing prevalence of Lyme disease (LD) and emergence of other tick-associated human diseases in the United States have become a major public health concern. Ticks are nuisance pests that can cause severe toxic allergic reactions and are vectors of numerous viruses, bacteria, and protozoa that can impact humans, companion animals, and domestic livestock (Jongejan and Uilenberg 2004). There are over 20 recognized human diseases or clinical conditions associated with ticks in the United States. Blacklegged ticks, *Ixodes scapularis* Say (Ixodida: Ixodidae), are the primary vector of at least seven pathogens that cause human diseases, including *Borrelia burgdorferi* Johnson et al. 1984 emend. Baranton et al. 1992 (Spirochaetales: Spirochaetaceae) (the causative agent of LD), *Babesia microti* (Aconoidasida: Piroplasmida) (human babesiosis), *Anaplasma phagocytophilum* (Foggie 1949) Dumler et al. 2001 (Rickettsiales: Ehrlichiaceae) (human granulocytic anaplasmosis), *Borrelia miyamotoi* Fukunaga et al. (Spirochaetales: Spirochaetaceae) (hard-tick relapsing fever) (Krause et al. 2013), *B. mayonii* (new Lyme *Borrelia* spp.) (Pritt et al. 2016), *Ehrlichia*

muris-like agent (ehrlichiosis) (Pritt et al. 2011), and Powassan or deer tick virus (Powassan encephalitis) (Ebel 2010, Hermance and Thangamani 2017). Since LD was first described in the 1970s, the number of reported human cases in the United States has steadily increased, largely due to the range expansion of *I. scapularis* and spread of *B. burgdorferi* (Diuk-Wasser et al. 2012, Pepin et al. 2012, Kugeler et al. 2015, Eisen et al. 2016). The actual incidence of human disease cases is estimated to be at least 10-fold greater than reported confirmed and suspected cases at ≈329,000 annually (Hinckley et al. 2014, Nelson et al. 2015). Blacklegged ticks may also be co-infected with two or more pathogens resulting in multiple tick-associated infections from a single or several tick bites (Hersh et al. 2014, Diuk-Wasser et al. 2016).

While *I. scapularis* and LD have been the impetus for recent research on tick ecology and management, the lone star tick, *Amblyomma americanum* (L.) (Ixodida: Ixodidae), is the primary tick encountered by humans in the southeastern U.S. and no longer simply a nuisance species (Childs and Paddock 2003, Paddock and Yabsley 2007, Stromdahl and

Hickling 2012). It is the vector associated with several *Ehrlichia* species (*E. chaffeensis*, *E. ewingii*, and the Panola Mountain *Ehrlichia* or PME), southern tick-associated rash illness or STARI, a red meat allergy, and possibly tularemia (caused by *Francisella tularensis*) and spotted fever rickettsiosis (caused by *Rickettsia rickettsii* and *R. parkeri*), as well as the newly discovered Heartland virus and Bourbon virus. The American dog tick, *Dermacentor variabilis* (Say), and Rocky Mountain wood tick, *D. andersoni* (Stiles), and more recently, the brown dog tick, *Rhipicephalus sanguineus* (Latrille) (Ixodida: Ixodidae), are vectors of pathogens causing tularemia and spotted fever rickettsiosis, particularly, *R. rickettsia*, the agent for the Rocky Mountain spotted fever.

A wide variety of prevention and control strategies have been utilized or investigated to reduce tick abundance, the prevalence of tick-borne pathogens, and/or the risk of human exposure to tick-associated pathogens (Stafford and Kitron 2002, Ginsberg and Stafford 2005, Stafford 2007, Piesman and Eisen 2008, Eisen and Dolan 2016). These strategies can be broadly divided into personal protection measures (i.e., repellents, protective clothing, tick checks, and tick removal) or tick management approaches with the objective of reducing contact between ticks and humans, reducing tick abundance or lowering the prevalence of tick-borne agents in the ticks. Alternatively, tick management approaches can be classified by method (e.g., spraying or host reduction) or target (e.g., tick, pathogen, or host). These various methods include landscape and habitat modifications, application of acaricides, biological control agents (e.g., predators, parasitoids, nematodes, or pathogens that may be classified by the U.S. Environmental Protection Agency (EPA) as a biopesticide), reproductive host reduction or exclusion, host-targeted acaricides to tick reproductive or pathogen reservoir hosts, host-targeted Lyme vaccines, and anti-tick vaccines (Table 1). Some methods may conceptually overlap. The use of chemical acaricides has long been the principal method for controlling ticks on domestic animals or in the environment. Tick control products may include synthetic pesticides, botanical extracts and/or compounds, or entomopathogenic organisms such as the recently introduced entomopathogenic fungus, *Metarhizium brunneum* (Petch) (Hypocreales: Clavicipitaceae) Strain 52 (*M. anisopliae* F52) (Met52, Novozymes Biological Inc., Salem, NC), formulated as an EPA registered biopesticide. Semiochemicals; pheromone, kairomones, and attractants, could be used to enhance acaricide efficacy or reduce pesticide concentrations (Sonenshine 2006). Generally, these approaches for the control of *I. scapularis* have been applied in the field by commercial applicators or evaluated for efficacy by investigators as a single intervention, comparisons between single interventions, or less commonly a combination of two or more approaches (Eisen and Dolan 2016). However, it is increasingly apparent that under most circumstances, no one method is likely to be universally acceptable to homeowners or provide sufficient suppression of tick abundance or the prevalence of the pathogen in the vector or reservoir host in order to prevent human disease.

There are numerous reasons for the lack of success in tick bite prevention and control of ticks and tick-borne diseases (Eisen et al. 2012). The ecology of ticks and tick-borne diseases is complex and the behavioral factors influencing human risk for tick bite and exposure to tick-borne pathogens are still not fully understood. With few exceptions (e.g., substantial reduction or elimination of white-tailed deer, *Odocoileus virginianus* (Zimmermann) in geographically isolated areas), single intervention strategies are limited in duration or efficacy and cannot properly address the complexity of different vector life cycles, reservoir hosts, and human behavior and their intricate interactions. Furthermore, area-wide application of synthetic chemical acaricides is becoming less acceptable due to perceived health hazards by the public. Consequently, there is increased interest in

Table 1. The "toolbox" for integrated tick management and tick-associated diseases – existing and potential strategies for personal protection, the control of host-seeking ticks, reducing pathogen prevalence, and reducing the risk of Lyme disease and other tick-associated illnesses

Personal protection measures	Avoid tick habitats
	Protective clothing
	Tick checks and prompt tick removal
	Synthetic chemical repellents
	'Natural' product-based repellents
	Permethrin-treated clothing
Treatment/vaccination humans	Antibiotic use after tick bite
	Human vaccine
Landscape/vegetation management	Xeroscaping/hardscaping
	Remove leaf litter and brush, mow grass
	Remove rodent harborage
Target host-seeking ticks	Synthetic chemical acaricides
	Botanically-based acaricides
	Biological agents and biopesticides (entomopathogenic fungi, nematodes, and other pathogens)
	Acaricides with semiochemicals as lures or decoys
Rodent-targeted approaches	Topical acaricide bait boxes
	Oral Lyme disease vaccine bait
	Oral antibiotic bait
	Oral tick growth regulator
Deer-targeted approaches	Topical acaricide self-treatment bait stations
	Deer reduction
	Systemic acaricides
	Deer exclusion (fencing)
	Oral tick growth regulator
	Anti-tick vaccine

Modified from Ginsberg and Stafford (2005) and Eisen and Gray (2016).

adapting integrated management approaches (Beard and Strickman 2014). We hereby review human risk for tick-borne disease and concepts related to tick population management and control strategies available within the framework of integrated tick management and control for the prevention of tick-associated diseases.

Risk of Tick-Associated Diseases

The risk of human exposure to tick-borne pathogens will vary with tick abundance, different spatial and temporal patterns of tick distribution and activity, landscape patterns and habitat type, and various human activities and behaviors that expose people to host-seeking ticks. Better understanding of human activities and behaviors, particularly in residential settings, that may expose them to tick bites and consequently the risk of disease is required (Eisen et al. 2012, Eisen and Eisen 2016). Demographically, the greatest incidence of LD is for the age groups of 5–9 and then 60–64 (Centers for Disease Control and Prevention 2008, Nelson et al. 2015, 2016). There appears to be a slight shift in the recent LD statistics from Connecticut with a greater incidence occurring in the 70+ age bracket (Fig. 1). These statistics align with the estimated peridomestic, high-risk activities such as play and yard work in residential properties, and known distribution of *I. scapularis* in peridomestic habitats (Maupin et al. 1991, Carroll et al. 1992, Stafford and Magnarelli 1993). In the northeast, *I. scapularis* comprises the majority of human-tick encounters. The vast majority of tick species submitted
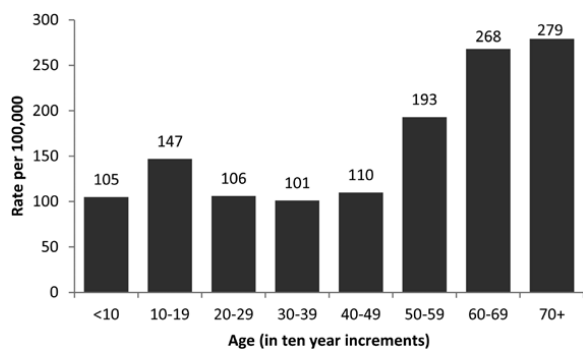
Fig. 1. Lyme disease incidence by 10-yr age groups, Connecticut, 2015 (data courtesy of Connecticut Department of Public Health).

Fig. 2. Likelihood for acquiring an *I. scapularis* tick bite in the residential environment based on a Stamford Health Department, CT survey of 4,717 tick submissions to the Tick Testing Laboratory at the Connecticut Agricultural Experiment Station, 1989–2001: (A) location, (B) activity.

to the Connecticut Agricultural Experiment Station (CAES) Tick Testing Laboratory are *I. scapularis* (92.5% of 93,959) with *D. variabilis* (5.9%) and *A. americanum* (1.3%) of the ticks received during 1996–2016. A health department survey (Stamford, CT Health Department, *n* = 4,717 records) conducted during 1998–2001 in conjunction with ticks removed from humans and submitted to the CAES Tick Testing Laboratory for *B. burgdorferi* testing found that 74% of ticks were reportedly acquired around the home, 21% from activities away from the home, 5% from the neighborhood, and 0% from inside the home (Fig. 2). The highest identified risk activity was play (47% of respondents), followed by yard work (18%), and gardening (12%). Activities away from the home included hiking (7%), an outdoor job (5%), and walking the dog (4%). The time engaged in activities with greater exposure to ticks is unclear. The average time per day spent in lawn and garden care activities by the civilian population was 1.88 and 2.25 h on weekdays and weekends and holidays, respectively, in 2015 (U.S. Department of Labor 2017). This pattern of activities has changed not changed substantially since 2005, the furthest past year statistics appear readily available. However, time spent outdoors near vegetation was significantly associated with positive Lyme serology (Finch et al. 2014).

In contrast to the Northeast, occupational and outdoor activity (walking in the woods, or leaning against logs and trees) in California comprise the greatest exposure to the western blacklegged tick, *I. pacificus* (Cooley and Kohls) (Ixodida: Ixodidae), and possibly for *A. americanum* in the southeastern U.S. (Lane and Lavoie 1988, Clover and Lane 1995, Lane et al. 2004, Eisen et al. 2016). Interestingly, the abundance of *D. variabilis* appears to be decreasing in some areas where *A. americanum* populations have notably increased (Stromdahl and Hickling 2012), potentially changing the dynamics for risk for certain tick-borne diseases. It is unclear whether the majority of tick bites by *A. americanum* is acquired peridomestically or is associated with recreational and similar activities, but all stages feed on humans and multiple tick bites are common. The vast majority of ticks (>95%) removed from humans in southeastern states are *A. americanum*. The risk for exposure to other tick species and associated pathogens is also increasing in parts of the United States. The range of the Gulf Coast tick, *A. maculatum* (Koch) (Ixodida: Ixodidae), the primary vector for *R. parkeri* rickettsiosis, and long considered primarily a veterinary pest, is expanding in the southeast and appears to be feeding on humans more frequently than previously believed (Paddock and Goddard 2015).

Classic IPM and Economic Thresholds

Classic integrated pest management or IPM involves the selection, integration, and implementation of several pest control actions based on predicted ecological, economic, and sociological consequences
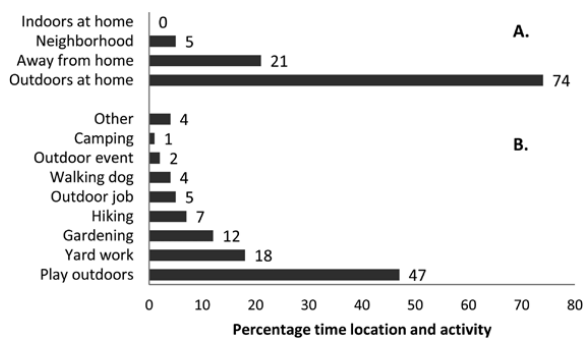
(Rabb 1972). The objective of IPM is to reduce the density of a pest to a level below the economic injury threshold, the density at which losses exceed cost of control (a cost–benefit analysis; i.e., impact on production). For example, an economic threshold for *A. americanum* in recreational areas was proposed at 0.65 ticks per 1-h carbon dioxide sample based on attack rate of <1 tick per human visitor per day (Mount and Dunn 1983). However, management decisions for nuisance ticks or for tick-associated diseases is not merely an economic one (although the cost burden of disease could be considered), but usually a cost-efficiency analysis for the allocation of resources to lower the number of ticks or the number of infected ticks and the number of human disease cases (Stafford 1993). The purpose of tick management can broadly be defined as protecting either a commodity, such as ticks on livestock or nuisance ticks in a recreational area, or managing the risk of tick-associated diseases for humans. Classic tick population management implies an acceptable level of pest abundance and either an acceptable level of damage or loss (i.e., for humans – the risk of disease or actual cases of disease) or a threshold below which there is little or no disease transmission.

Success of approaches to prevent tick-associated diseases depends on reducing the probability of human infection by reducing exposure to ticks or infection prevalence in ticks (Ginsberg 1993). Lowering or eliminating disease risk means either reducing tick bites or pathogen prevalence to nearly zero or zero. However, the abundance of ticks infected with *B. burgdorferi* is not linearly related to human risk of tick bite exposure. Actual thresholds to maintain enzootic transmission of *B. burgdorferi* among reservoir hosts or prevent spillover to humans in various settings remain unclear. Integrating methods that have the same effect on reducing tick abundance or pathogen abundance would theoretically be more effective than using these methods individually (Ginsberg 2001), but few studies have examined an integrated tick and pathogen management strategy. Tick control methods may also have an immediate or a time-lagged impact requiring long-term follow-up (Eisen et al. 2012). Any integrated tick management program will require monitoring or assessing the associated risks and have measureable outcomes such as reduced entomological risk (i.e., abundance of infected ticks), fewer tick bites, or reduced incidence of disease. Most tick intervention studies evaluate outcome in the context of entomological risk. Assessments based on the incidence of actual human disease are logistically more difficult or expensive, and only a few studies have documented or attempted to document an impact on tick encounters or human LD cases (Garnett et al. 2011, Kilpatrick et al. 2014, Hinckley et al. 2016), albeit with some drawbacks.

Knowledge, attitude, and behavior (KAB) surveys show that most people consider LD to be of high or very high concern and the likelihood of a family member getting this disease high (Shadick et al. 1997, Gould et al. 2008, Bayles et al. 2013). But there is variability in acceptance, affordability, and use of various interventions, such as repellents, protective clothing, tick checks, or environmental tick control measures. Over half of the respondents (51.2% of 4,050) in national HealthStyles surveys reported not routinely taking personal prevention steps against tick bites (use repellent, shower, do tick checks) and even fewer (10.7% of 4,728) used yard pesticides to control ticks, although a relatively high percentage of those surveyed reported exposure to ticks (e.g., 29.8% in New England, 24.0% in the mid-Atlantic, and 25.4–32.2% in southeastern states) (Hook et al. 2015). Although the use and efficacy of various prevention measures has been mixed (Phillips et al. 2001, Vazquez et al. 2008, Connally et al. 2009, Finch et al. 2014), protective clothing, checking for ticks, bathing within 2 h of tick exposure have been found to be preventive for LD. Despite evidence that personal protection measures can be effective, less than half of the public in the HealthStyles surveys used preventive measures (Hook et al. 2015). A previous history of tick bite or frequent detection of ticks appears important in the adoption or use of prevention measures (Shadick et al. 1997).

In an earlier KAB study in several health districts in Connecticut (Gould et al. 2008), 35% of respondents reported never using an environmental tick control method. Although use of acaricides was higher (64%) than in national surveys, cost was a major factor with 19% unwilling to spend money on tick control, 44% would spend up to $100, and 30–48% willing to spend ≥$100, which seemed to reflect, in part, community affluence. There is also growing interest in organic land care practices that preclude the use of synthetic acaricides, certain synergists, and any pesticide formulated with an inert ingredient on the EPA's list of inert ingredients of toxicological concern (Cunningham 2007). National organic standards do not apply to land care, although some materials may be listed by the Organic Materials Review Institute. Current "natural" (the term natural has no legal definition) products for tick control are limited and few have been evaluated for efficacy (Rand et al. 2010, Elias et al. 2014, Bharadwaj et al. 2015). These are largely based on botanical essential oils or plant extracts on the EPA's FIFRA 25-b list of generally recognized safe compounds. Identifying barriers to adoption of personal protection measures and environmental tick management is one question that needs to be addressed to help understand the lack of success in the prevention and control of LD (Eisen et al. 2012).

Current State of Integrated Tick Management

There are a limited number of integrated tick management studies particularly for *A. americanum*, and more recently, for *I. scapularis* (Eisen and Dolan 2016). Earlier studies for area-wide tick management in non-agricultural areas were for *A. americanum* using acaricides, vegetation management, and exclusion of *O. virginianus*. These three control methods were applied either individually or in some combination in a recreational area in Tennessee (Bloemer et al. 1990). Suppression of tick abundance was greater with various combinations of integrated strategies than with each method alone. Combinations of acaricide applications and vegetative management; acaricide applications and host management; and acaricide applications, vegetative management, and host management produced 94, 89, and 96% average control, respectively, of all life stages of *A. americanum*. Fencing had high upfront costs, but was the most economical when prorated over the expected 10 yr life-expectancy of the structure. Annual vegetation management was the most

expensive method, especially when combined with two acaricide applications. However, acaricides or vegetation management alone was not able to reduce the relatively high densities of *A. americanum* below economic threshold levels. The adopted strategies also depended on tick densities with all three techniques utilized together providing the greatest control of the highest tick densities (92–99%). Deer exclusion alone was less effective in controlling nymphs and adults than the other two methods alone due, in part, to the time lag for populations to decrease because of the long tick life cycle and introduction of engorged subadult ticks by small avian and rodent hosts.

Schulze et al. (2007, 2008) examined the integrated use of four posters, fipronil-based rodent bait boxes, and a barrier application of granular deltamethrin in Millstone, NJ for residential control of *I. scapularis*. The larval and nymphal tick burden of *I. scapularis* on white-footed mice, *Peromyscus leucopus* (Rafinesque), was reduced by 92.7 and 95.4%, respectively. The control of host-seeking nymphs, larvae, and adult *I. scapularis* was 94.3, 90.6, and 87.3%, respectively. An integrated tick management study in Connecticut conducted from 2013 to 2016 incorporated deer reduction, fipronil rodent bait boxes, and barrier applications of the entomopathogenic fungus *M. brunneum* (*M. anisopliae*) will provide additional information on the efficacy of an integrated approach in different settings. While interference from local hunters prevented sufficient deer removal to negatively impact *I. scapularis* abundance, preliminary analyses indicate sustained combination of rodent-targeted bait boxes and barrier application of *M. anisopliae* significantly reduced questing nymphal *I. scapularis* and *B. burgdorferi*-infected nymphal *I. scapularis*, and tick burdens on *P. leucopus* (S.C. Williams, K.C. Stafford, and G. Molaei, unpublished data). The USDA-Agricultural Research Service has provided funding for a 5-yr integrated tick management project incorporating rodent bait boxes, *M. brunneum* applications, and four posters in MD and CT that will provide additional much needed empirical data on the efficacy of various combinations of these control measures (Kaplan 2017). Other new integrated tick management studies include projects in western CT (Western Connecticut State University 2016) and New York (Cary Institute of Ecosystem Studies 2016) in New York supported by the Centers for Disease Control or Prevention or the Cohen Foundation. These various studies will provide additional important information on the application and efficacy of different combinations of tick control technologies at different geographical scales and ecological settings.

An integrated approach is supported by earlier computer simulation models that had been developed to examine the population dynamics of *D. variabilis*, *A. americanum*, and *I. scapularis*, and then applied to various management strategies for these species, albeit with assumed conditions not always found in field trials. Simulations (LSTSIM) with individual and combined strategies of *A. americanum* populations in non-agricultural areas looked at area-wide acaricide applications, vegetation reduction, deer density reduction (exclusion), treatment of deer with a systemic acaricide, and self-treatment of deer with a topical acaricide and compared them with observed studies (Mount et al. 1999). A combination of vegetation reduction and two acaricide applications to all of the target area provided the best short term, seasonal management of ticks for residential sites with 87–95% reduction of ticks on hosts in the first year, but these higher levels of control were dependent on treating 100% of the managed area. The specific combinations of interventions, level of intervention, or number of years an intervention was applied (e.g., 50% habitat sprayed, 15 or 25% of habitat with vegetation reduction, 70% deer reduction, and/or 70% kill of ticks on deer from acaricide self-treatment) determined the

number of years required to reduce *A. americanum* nymphs below a set tolerance threshold. Multiple acaricide treatments, which rapidly reduce tick abundance, followed up by the longer-term methods was the best long-term strategy. The simulated results compared well with observed reductions of *A. americanum* densities from earlier studies with 100% application of the various control technologies. Interestingly, the complete elimination of deer in the simulation reduced nymphal *A. americanum* below the set tolerance threshold by the second year and eliminated the tick population by year 8.

A similar simulation model (LYMESIM) was used to examine the population dynamics and various individual and combinations of management strategies for *I. scapularis* (Mount et al. 1997a, b). The authors considered area-wide acaricide, acaricide treatment of white-footed mice (permethrin-treated cotton) and white-tailed deer (systemic or topical), vegetation reduction, and deer density reduction. The fipronil-based rodent bait box approach was not yet developed (Dolan et al. 2004). Area-wide acaricide applications, vegetation reduction, or a combination of the two were found useful for short-term control in small recreational or residential settings, while the treatment of deer was the most cost-effective strategy for larger areas. The use of two combined control strategies could reduce densities of infected nymphs by >90% and below a modeled transmission threshold. Application of the LYMSIM model to a hypothetical residential community also found the treatment of deer to be most effective single intervention in preventing the most LD cases except for best use scenario of an LD vaccine (Hayes et al. 1999). However, there are logistical and practical issues with the treatment of deer. The complete removal of white-tailed deer from Mohegan Island, ME resulted in a substantial decline in *I. scapularis* on the island within 3 yr, after which a few ticks appeared to be derived from migrating birds (Rand et al. 2004, Elias et al. 2011). Newer models using more recent data on tick population dynamics, hosts, efficacy of various combinations of interventions, human exposure elements, and the utilization of personal protection and environmental measures by people are helping to better understand the interactions of integrated strategies for tick management.

While it is clear that an integrated management approach is likely the best strategy to control ticks and tick-associated diseases in the absence of human vaccines, continued information and education of both the public and professionals should be part of integrated control strategies. Because many tick-borne diseases are caused by zoonotic agents and may affect wildlife, companion animals, livestock, and humans, Dantas-Torres et al. (2010) argue that increased education and communication between physicians and veterinarians is essential to address tick-associated diseases in a 'One Health' approach and unify the animal and human branches of medicine to identify, treat, and implement preventive measures. The One Health concept is not new, but is particularly applicable for zoonotic and vector-borne diseases (Centers for Disease Control and Prevention 2017). Not only can the presence of tick-associated diseases in companion animals can act as a sentinel for the risk of human disease, but also control of ticks on companion animals should be part of an overall integrated approach to managing ticks. A striking example was community-based control of *R. sanguineus* and an outbreak of Rocky Mountain spotted fever on an American Indian reservation in Arizona in which long-acting tick collars and animal care practices played a major role in the overall tick management program (Drexler et al. 2014). Dantas-Torres et al. (2010) rightly point out that medical or veterinary clinicians rarely are trained or knowledgeable about tick identification, and a KAB survey of primary care physicians found a lack of awareness about diagnostic criteria, management of tick bite, and the empiric treatment of unsubstantiated

LD (Magri et al. 2002). Entomologists, vector ecologists, tick control personnel and pest management professionals, modelers, public health professionals, and other disciplines are all needed to address increasing and emerging tick-associated diseases.

We have many tools in our tick-associated disease management toolbox that target host-seeking ticks, host-feeding ticks on animal reservoirs and reproductive hosts, pathogen prevalence in vectors and reservoir hosts, and directly reduce human tick-bite encounters (Ginsberg and Stafford 2005, Eisen and Gray 2016) (Table 1). Some are experimental, have had limited application, and others (such as an oral rodent LD vaccine) may be close to licensing and more generally available (Richer et al. 2014). Many questions remain related to the ecology of ticks and tick-borne pathogens, observed and modeled efficacy of various integrated interventions, human behavior and exposure to tick-bite and disease risk, comparative cost of interventions, and acceptance and use of prevention and tick control tools. Some approaches are readily available to the residential homeowner (i.e., acaricide applications, vegetation management), while other technologies would require or be more effective with community-level participation (i.e., host-targeted technologies, deer reduction). The costs associated with wide-area technologies would need to be shared between homeowners and local communities. Nevertheless, despite the impact of rodent bait boxes and other technologies, tick control for residential properties will likely continue to largely rely on the area-wide application of acaricides and cost will continue to be a major consideration.

Acknowledgments

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